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The effect of temperature on the tensile properties of HSLA-100 steel.

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THESIS

THE EFFECT OF TEMPERATURE ON THE TENSILE
PROPERTIES OF HSLA-100 STEEL

by

James E. Hamilton

June 1987

Thesis Advisor: Kenneth D. Challenger

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Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True

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The Effect of Temperature on the Tensile Properties of HSLA - 100 Steel

by

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Lieutenant, United States Navy
B.S.M.E., University of Colorado, 1979

Submitted in partial fulfillment of the
requirements for the degree of

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June 1987

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Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True stress, corrected for necking, and true plastic strain were monitored throughout the tests. This allowed a comparison to be made between the plastic strain behavior of HSLA - 100 steel and a traditional constitutive equation used to describe the stress-strain behavior of metals.

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I. INTRODUCTION

A. DEVELOPMENT OF COPPER BEARING HSLA STEELS

The problems associated with welding quenched and tempered high alloy and plain carbon steels are well documented [Refs. 1,2]. The high cost of manufacturing and producing satisfactory critical welds in these conventional steels combined with the desire for higher strength weldable materials has led to the development of High Strength Low Alloy (HSLA) steels. These steels utilize small microalloying element additions while keeping carbon below 0.15% to develop the desired strength and toughness levels.

The variety of steels classified as high strength low alloy (HSLA) has expanded greatly over the past decade. Orginally the classification applied strictly to carbon - manganese steels which were microalloyed with niobium, vanadium or titanium. The category of HSLA steels now includes acicular ferritic or low carbon banitic steels, higher carbon more pearlitic steels, quenched and tempered steels, dual phase steels, and cold rolled and tempered steels. This paper will deal with acicular ferritic HSLA steels where copper is the primary strengthening microalloying constituent. When referring to HSLA steels herein this is the intent.

The ability of Cu additions to strengthen steels has been know since the 1930's; however, commercial development and production was slow to proceed until the late 1960's [Ref. 3]. The key reason for the slow progress in developing this type of HSLA steel was the deterioration of the hot working properties of Cu bearing steels [Refs. 4,5]. Once the problem of "hot shortness" was overcome a rapid development of a variety of Cu bearing HSLA steels followed.

During the 1970's several Cu bearing low alloy steels with similar chemical compositions were developed and tested. Various trade names are: NICOP, IN-787, and NICUAGE TYPE 1. High yield strength, above 70 KSI, improved weldability, toughness, ductility, and corrosion resistance over conventional steels has been reported for these new HSLA steels. [Refs. 6,7,8]

The military has certified a low alloy Copper - Nickel steel for structural uses, which is quite similar to the above mentioned commercial steels, designated HSLA - 80. The chemical composition of HSLA - 80 (MIL-S-24645) is listed in Table I of Appendix A which is taken in it's entirety from Reference 9.

B. INFLUENCE OF ALLOYING ELEMENTS ON HSLA STEELS

A portion of the Fe-Cu phase diagram is shown in Figure 1 [Ref. 10]. Wilson [Ref. 5:pp. 164-165] has verified that a sufficiently hardenable Fe-Cu alloy can be made to transform

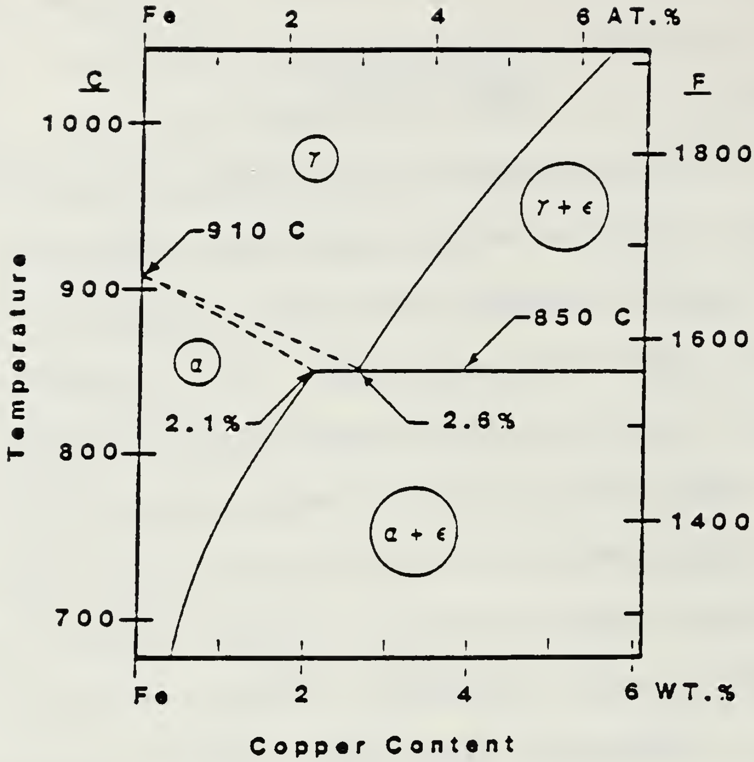


Figure 1. Iron Rich End of the Fe-Cu Phase Diagram

from the austenite region to form martensite and supersaturated ferrite. As the solubility of copper in ferrite is less than in austenite some copper may precipitate in the ferrite however, the equilibrium solubility is not reached on cooling. Subsequent aging heat treatment then produces high strength levels by uniform precipitation of a copper rich epsilon phase which appears as rods or spheres. Quenching from elevated austenitizing temperatures causes significantly more copper to remain in solid solution than air cooling. The subsequent precipitation of epsilon copper particles in the ferrite by

heat treating provides the primary strengthening mechanism of this type of HSLA steel. [Refs. 11,12]

The microstructure of HSLA - 80 (Class 3 - quenched and aged) varies, (depending on cooling rate from the austenitization temperature), from polygonal/acicular ferrite at high cooling rates (thin plates) to a polygonal ferrite matrix with dispersed groups of cementite particles for slower cooling rates (thicker plates) [Ref. 10:pp. 7-12]. Steels with acicular ferrite microstructures exhibit much higher strength than those with polygonal ferrite microstructures [Ref. 13]. Acicular ferrite, synomymous with bainitic ferrite, differs from polygonal ferrite in that acicular ferrite exhibits lath like ferrite grains containing a high dislocation density. A key addition to HSLA - 100 is niobium. Its addition to these copper bearing steels is primarily for grain size refinement. This is accomplished in two ways, by the precipitation of niobium carbonitrides during the austenitization (class 3 plates) process and by retarding austenite recrystallization during hot rolling [Ref. 12:pp. 656-659]. Niobium also provides some precipitation hardening effect.

In these steels the potential problem of hot shortness, the formation of low melting point copper rich phases which can cause fissured surfaces during thermal mechanical processing, is prevented by nickel additions to copper bearing steels. However, the primary reason nickel is added

to these steels is its beneficial effect on toughness. As with niobium, a strength increase is also observed with nickel additions. Finally, since nickel remains with copper during remelting, scrap can be used in melts of other steels without the potential harmful effects of copper alone [Ref. 14].

Chromium and molybdenum are necessary to retard the epsilon copper precipitate nucleation and growth, during quenching form the austenitizing temperature, known as auto-aging. This enables closer control of the finished product and thus more consistency in mechanical properties. [Ref. 15]

Manganese, as with chromium and molybdenum helps to suppress polygonal ferrite formation, thus adding transformation substructure strengthening to these steels' overall strengthening components [Ref. 10:pp. 3-4]. Manganese increases the hardenability of HSLA steels as it does conventional steels.

Silicon is added as a deoxidizer and the aluminum present acts to enhance grain refinement. Impurity elements such as phosphorous and sulfur are kept to a minimum by direction in the military specification for HSLA - 80. The concern with phosphorous is embrittlement caused by the formation brittle iron and nickel phosphides [Ref. 1: p. 98]. Sulfur is kept as low as possible because a steel's susceptability to lamellar tearing is proportional to the

sulfur content [Ref. 16]. This is accomplished by a low sulphur practice such as vacuum degassing and argon injection with CaSi or Mg for sulfide shape control, as specified in Appendix B.

C. INFLUENCE OF HEAT TREATMENT ON HSLA STEEL PROPERTIES

The ASTM heat treatment applicable to the copper bearing HSLA steels discussed herein is Class 3 (quenched and precipitation hardened). For HSLA - 80 the austenitizing temperature range is 870 to 970 C (1600 to 1700 F). After water quenching, approximately 450 Mpa (65 Ksi) of the total expected 550 MPa (80 ksi) yield strength is attained. Precipitation hardening at 540 to 665 C (1000 to 1225 F) supplies the remaining portion of the desired yield strength. This precipitation strengthening more than offsets any softening occuring at the precipitation heat treatment temperature. [Ref. 12:p. 656]

1. Temperature effect on precipitation hardening

In order to achieve the desired levle of strength, toughness and weldability of the precipitation hardenable steels, various aging temperatures/times are used. There are three ASTM classifications for precipitation hardenable steels. Class 1 desiginated as-rolled plus precipitation hardened, yields the highest strength levels. Class 2 is normalized plus precipitation hardened, this produces a lower strength than Class 1 but improved toughness. Class 3

is quenched plus precipitation hardened, this Class provides the best overall level of toughness with strengths comparable to Class 1. As noted earlier a Class 3 precipitation heat treatment is required to provide the fine grained acicular ferrite microstructure. Jesseman and Murphy [Ref. 12:pp. 656] note that at this stage of production "the relatively soft as-rolled, as-normalized or as-quenched conditions have good ductility and moderate toughness. Cold forming at this stage is sometimes advantageous because lower press capacities are required." Then precipitation heat treating can ameliorate the effects of straining and aging on toughness. It is noteworthy that post weld precipitation hardening can serve as a simultaneous stress relief thus reducing overall fabrication costs [Ref. 3:pp. 445-449]. Since diffusion of copper in ferrite is involved in the strength determination of these steels, both the time and the temperature of the precipitation heat treatment is important. Jesseman and Murphy [Ref. 12:pp. 657-658] concluded that treating above 565 C (1050 F) produced a gradual softening. The rate of this softening was slow, due to the additions of molybdenum and chromimum, and thus easily controllable. Additionally, raising the precipitation heat treatment temperature to 595 C (1100 F) or above markedly improved CVN impact energy in Class 2 and Class 3 plates.

2. <u>Time effect on precipitation hardening</u>

The mechanical properties of copper bearing HSLA steels are largely determined by the size and amount of the epsilon-copper precipitates. These in turn are governed by the aging treatment. The workers in Reference 17 report that overaging is desirable. Overaging promotes high toughness and it reduces the sensitivity of the steel to additional heating below the austenitizing temperature which could occur during welding or bending/shaping operations. Also, overaging was reported to lead to high toughness. Testing reported in Reference 12 revealed that the effect of time at aging temperature was notably less significant than the effect of temperature itself. Similar results were reported in Reference 17, where Class 3 steels only underwent a small change in properties when the aging time was varied thirty minutes at 899 C (1650 F). Several papers in the Conference Proceedings of International Conference on Technology and Applications of HSLA Steels 3-6 October 1983 Philadelphia, Pennsylvania noted that degraded mechanical properties were restorable by reaustentization and aging treatment.

II. BACKGROUND

A. STRESS - STRAIN RELATIONSHIPS

Many mathematical formulations have been developed to relate stress and strain in metals. Historically the relations developed attempted to relate stress - strain behavior from the onset of loading to the point of fracture. No single relation has gained universal acceptance due to problems associated with describing elastic and plastic behavior in a single equation. As a result, although many expressions have been developed since Hooke's law was introduced in 1678, many are of limited utility [Ref. 18].

When a material has experienced plastic deformation the linear relationship between stress and strain, described by Hooke's law, is no longer applicable. Figure 2 depicts a general stress - strain diagram for a material without a pronounced yield point [Ref. 19]. The figure depicts the elastic region and two regions of plastic deformation. In the elastic range stress is directly related to strain through a constant of proportionality. Hooke's law can be expressed as:

$$S = E\ e$$

Where S is the applied stress and e the engineering strain is the change in specimen length divided by the original length. The constant of proportionality, E, is a measure of

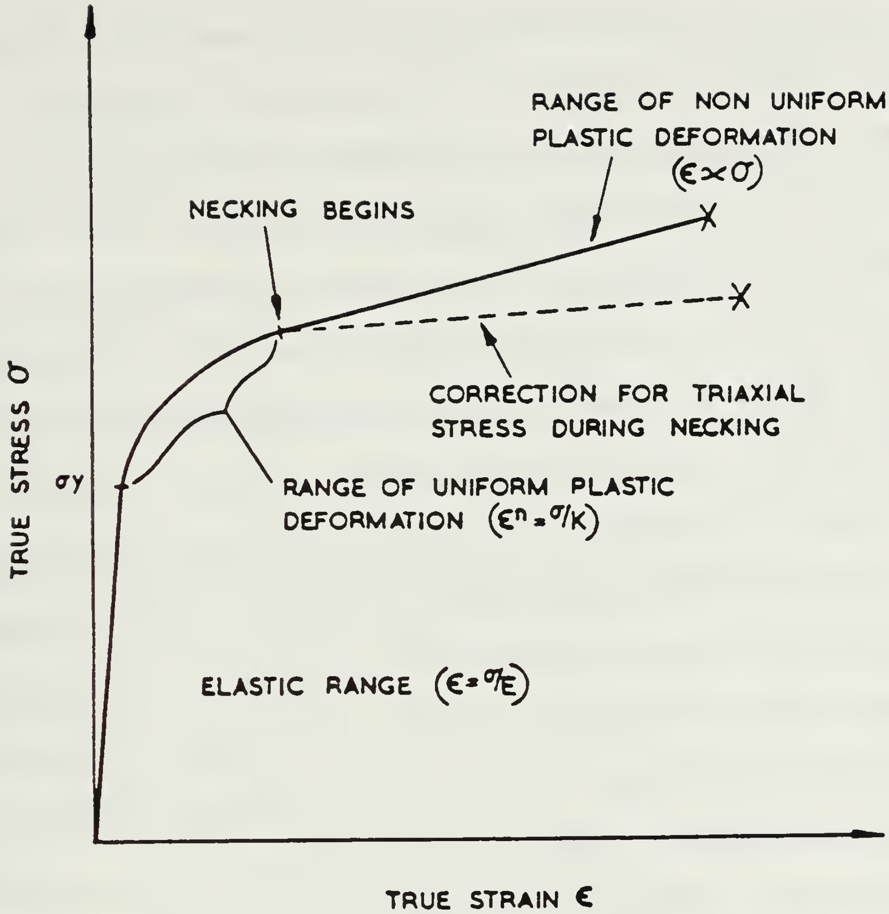


Figure 2. True Stress-True Strain Curve for a Metal without a Pronounced Yield Point

the materials stiffness and is referred to as Young's modulus or the modulus of elasticity. Once the yield stress, generally taken to be the stress necessary to produce 0.2% plastic strain, is exceeded the load necessary to produce further plastic deformation increases. The material is then undergoing strain hardening, by plastic deformation. In this region between the yield stress and the onset of specimen necking stress has been related to strain by expressions such as the Holloman equation [Ref. 20], as shown in Figure

2. The range of nonuniform plastic deformation begins when a localized neck develops in the weakes portion of the specimen. This neck causes a decrease the specimen cross-sectional area; thus resulting in a decrease in load. The load reaches a maximum at the onset of necking, because the decrease in cross-sectional area offsets the strengthening produced by strain hardening. In this region of the curve the relation between stress and strain becomes more complicated to express mathematically. The development of the neck causes a triaxial stress state to exist instead of uniaxial tension that existed up to the point of necking. In describing the relation between stress and strain in this region the stress resulting from the triaxial stress state must be accounted for. [Ref. 19:pp. 4-21]

In recent years, attention has focused on the development of analytical expressions for stress and strain in the region between the yield stress and the point where necking commences [Ref. 21]. A simple and commonly used expression relating stress and strain for a polycrystalline metal is the Holloman power function [Ref. 20:p. 374].

$$\sigma = K \epsilon^{n}$$

Where σ is the true stress and ϵ the true strain. K is a constant, representing the true stress at a true strain of unity, called the strength coefficient. When logarithms of

this power function are taken and true stress plotted versus true strain a straight line fit is predicted. The slope of the line has a value of n, the strain hardening exponent. Conway [Ref. 21: p. 156] notes that, although the equation calls for the use of true strain, "more consistency seems to be observed when true plastic strain is used". In this research the Holloman equation has been tested using the true plastic strain data obtained in testing HSLA- 100.

B. INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES

The strain hardening exponent, n, is a function of the materials strength level, chemical composition, and microstructure [Ref. 21: p. 157]. A high yield strength is achieved when dislocation motion is impeded initially. Dislocation motion is impeded by obstacles to their movement such as precipitates, impurities and other dislocations. Precipitates and impurities distort an otherwise perfect lattice and set up stress fields on the atomic level. When these stress fields interact with the stress field surrounding a dislocation its motion is impeded. Solid solution and precipitation strengthening are examples of mechanisms which take advantage of these stress field interactions to pin dislocations and thus strengthen a material. In addition to the above mentioned obstacles to dislocation motion, there is an inherent resistance within a crystal lattice to dislocation motion. This resistance is

termed the Peierls force and it is strongly related to the directionality of bonding of the material. A moving dislocation causes bond angle distortions. Covalent and ionic materials are strongly directional in their bonding. The bond angle distortion necessary for dislocation motion in these materials is thus difficult to overcome. In these materials the Peierls force is the primary obstacle to dislocation motion even when lattice vibration energy is enhanced at high temperatures. Body centered cubic materials develop a directional bonding component at low temperatures. The movement of dislocations in body centered cubic materials is thus strongly inhibited at low temperatures by the Peierls force. This effect is nullified at high temperatures where thermally enhanced atomic vibration overcomes the effect of the Peierls force. It is therefore expected that yield strength of HSLA - 100, a body centered cubic material, will exhibit rapidly increasing yield strength with decreasing temperature. An increase in yield strength in this manner will influence the strain hardening exponent. Figure 3 [Ref. 19: p. 33] illustrates this effect for molybdenum a body centered cubic material. [Ref. 22]

C. INFLUENCE OF STRAIN RATE ON TENSILE PROPERTIES

Strain rate can markedly affect the relationship between stress and strain in a similar way to temperature. In general the strain hardening exponent increases with

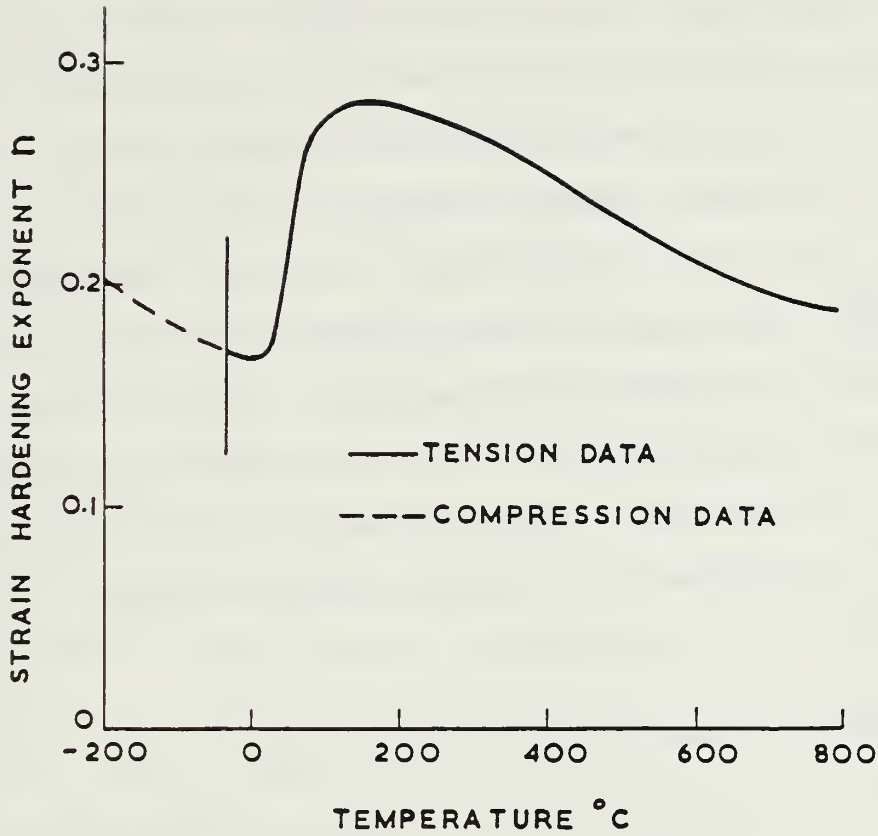


Figure 3. Strain Hardening Exponent of Molybdenum as a Function of Temperature

increasing strain rate [Ref. 21: p. 157]. With conventional tensile testing machines, where a constant loading rate is is imposed on specimen, the effect of necking is to increase the strain rate locally. The reduced cross-sectional area in the neck increases the strain and, as the loading is at a constant displacement rate, the strain rate increases. The rate of change of the strain rate continues to increase as the cross-sectional area decreases throughout the test. Tegart states that "the problems associated with necking are

accentuated at high testing speeds because adiabatic heating becomes localized in the necked region" [Ref. 19:pp. 37-38]. The experimental approach used in this research allows a tensile test to be conducted at constant strain rate. The rate of specimen diameter change, a direct measure of strain rate, is the controlling variable. Hourglass shaped specimens are used to ensure necking occurs at the minimum diameter. A diametral extensometer, fitted to the minimun diameter, continually follows the minimum specimen cross-section, providing feedback to the controlling system in order to maintain the constant rate of change of specimen diameter.

D. SCOPE AND OBJECTIVES OF PRESENT WORK

The nominal composition for HSLA - 100 steel is listed in Appendix A. Increased amounts of copper, nickel and manganese over that in the currently certified Navy steel HSLA - 80 provide the desired increase in yield strength, but before using this material in Naval ship construction, the resistance to brittle fracture must be evaluated and understood. Existing models for cleavage fracture of steels use the ever present iron carbides as crack initiation sites. However, the low carbon content (0.04%) of HSLA - 100 necessitates research to develop an applicable model. [Ref. 23]

Three regions of fracture behavior, ductile, transition and brittle, occur in steels [Ref. 23]. The terms ductile and brittle describe the amount of plastic deformation occuring at the tip of a crack propagating in a the steel. Ductile behavior, resulting from the nucleation, growth and coalesence of microvoids, is characterized by significant levels of plastic deformation ahead of the crack tip. In a brittle fracture very little plastic deformation at the crack tip is evidenced. In the tensile testing of steels, ductile behavior is observed above a certain critical temperature, and cleavage, primarily a brittle process, is observed below the critical temperature. The critical temperature is termed the Ductile to Brittle Transition Temperature (DBTT). [Ref. 25]

The transition from ductile to brittle fracture behavior occurs over a range of temperature in which the fracture is neither completely ductile nor completely brittle. As a ductile failure is normally preceeded by pronounced yielding it is desirable to have a low transition temperature. This precludes failure in a brittle manner, where cracks can propogate catastrophically. As strength levels in a metal are raised, by various means, there is a corresponding loss in the materials ductiliy. The loss of ductility leads to the fracture mode transition from ductile to brittle. Thus as strength increases, the DBTT for a given metal usually increases.

The DBTT for a particular steel is dependent on factors such as the chemical composition, microstructure, and crystal structure of the steel, as well as the temperature, state of stress, and strain rate at which it is tested. The chemical composition, effects of microalloying additions, and microstructure of HSLA - 100 are discussed with an emphasis on strengthening in the introduction to this work. With respect to DBTT, the effects of individual alloying elements is difficult to evaluate. However, in general nickel is observed to improve toughness and lower DBTT in steels containing less than 0.40% carbon. Interstitial atoms such as carbon and nitrogen can pin dislocations thereby increasing yield strength. Increasing the amount of these atoms present produces a loss of ductility and an increase in DBTT. The effect of the Peierls force on the yield strength of body centered cubic materials as temperature is decreased is discussed above. The increased yield strength of body centered cubic metals at low temperatures causes ductile to brittle transition. When the stress necessary to cause dislocation motion exceeds that for cleavage, brittle fracture results. Similarly, increasing the strain rate promotes brittle fracture because materials which exhibit a strongly increasing yield strength with decreasing temperature also exhibit an increasing yield strength with increasing strain rate [Ref. 22:pp. 211-214]. In order to remove the effect of increasing strain rate on

DBTT, the tensile tests in this research were conducted at constant strain rates as discussed previously. [Ref. 26]

The first phase in the fracture model development is to examine the quasi-static fracture behavior of HSLA - 100 steel. The objective of the present work is to develop the true stress - true strain tensile curves as a function of temperature. This information will be later used in a finite element analysis of the crack tip fracture behavior of this material.

III. EXPERIMENTAL PROCEDURE

A. MATERIAL

Appendix A lists the interim material specifications for trial commericial production of HSLA - 100 steel plates. A 32mm (1-1/4 inch) thick plate of HSLA - 100 steel (Plate # 5644-16B) meeting these specifications was prepared by the supplier. The plate was provided to the Naval Postgraduate School for examination by David Taylor Naval Ship Research and Development Center. The plate was heat treated by the supplier by austenitizing at 949 C (1650 F) for 70 minutes and water quenched; and subsequently aged at 615 C (1050 F) for 70 minutes and water quenched. This resulted in the strength properties reported in Table I, according to the supplier.

TABLE I

STRENGTH PROPERTIES OF PLATE # 5644-16B (AS REPORTED BY THE SUPPLIER)

	Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	% Elongation	% Reduction in area
Top Transverse	101	147	22	65
Bottom Transverse	106	139	23	65

B. TEST APPARATUS

In this research tensile tests were conducted with a Material Test System (MTS) 810 apparatus. On this system the loading is provided via a hydraulic actuator and grip assembly to a threaded specimen receptacle. A diametral extensometer was used to measure diametral diaplacement which was used as the test controlling variable. Load cell and extensometer output voltages were monitored by a digital voltmeter. The output voltages are converted to load and diametral displacement by a computer program. The computer program for collection of output data is listed in Appendix C. The frequency of sampling the output voltages by the digital voltmeter is determined by the collection program. If the user selects no additional delay between samplings the voltmeter is triggered by the computer to sample the output voltages from the MTS 810 at approximately 4 samplings per second. Thus when monitoring load, diametral displacement and hydraulic actuator piston stroke, all three channels from the MTS 810 can be sampled at least once a second. The program allows the flexibility to input an additional delay between samplings. In the testing conducted for this research no additional delay was requested for the first 50 samplings on all tests. In the intervals between 51 to 200, 201 to 400, and 410 to 500 nominal sampling delays were zero, 1 and 5 seconds respectively. The equipment used to conduct the tensile tests, collect, reduce and display

the output data are as follows:

1. MTS Closed-loop Electrohydraulic Testing System

   a) MTS Model 312.41 Load Frame
   b) MTS Model 661.21A -03 Load Cell (25 Kip)
   c) MTS Model 410.31 Function Generator
   d) MTS Model 506.20 Hydraulic Power Supply

2. MTS Model 651.1XA Enviromental Chamber (Modified)

   a) MTS Model 409 Temperature Controller
   b) MTS Diametral Extensometer Model 632.19B-21 (Modified)
   c) MTS Extensometer Model 613.20B

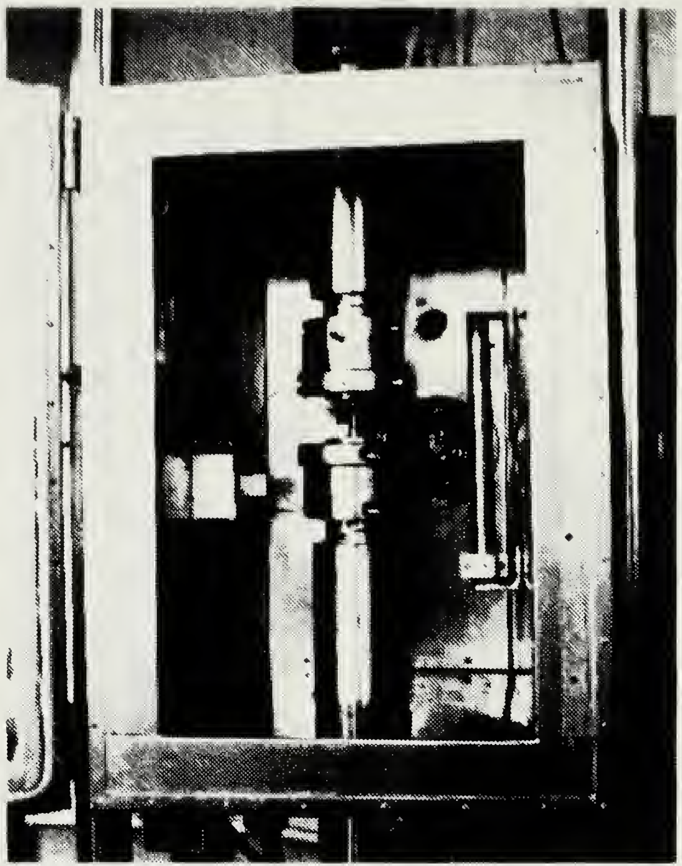
3. Hewlitt-Packard Data Acquisition System

   a) 9826 Computer
   b) 3497A Data Acquisition Control Unit (DVM)
   c) 3437A System Voltmeter
   d) 2617G Printer
   e) 7225B Plotter

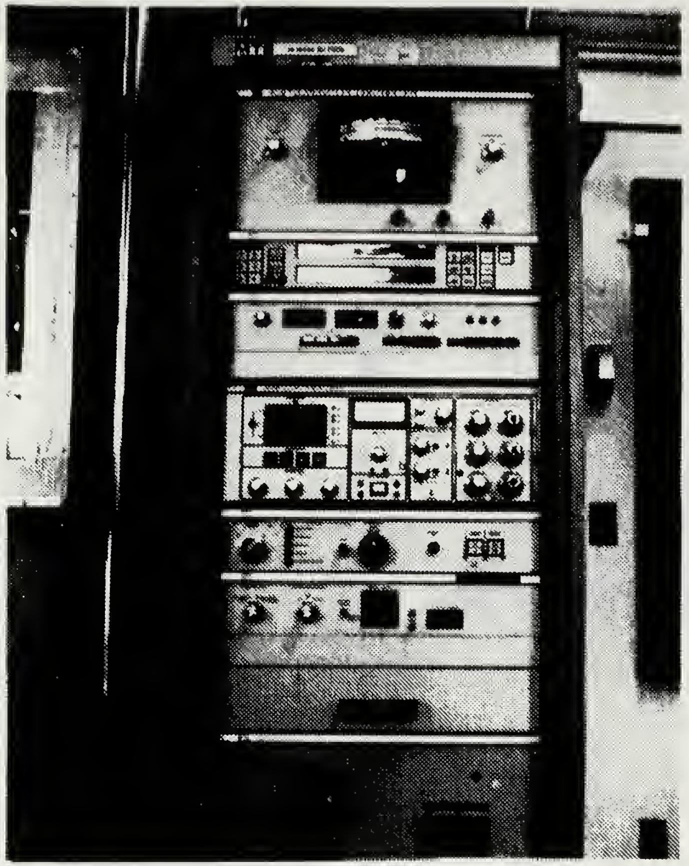
Figures 4a and 4b, are photographs of the testing system and Figure 5 is a photograph of the acquisition and reduction system used in this research. Figure 6 illustrates the enviromental chamber as modified. The enviromental chamber was modified to allow either liquid carbon-dioxide or liquid nitrogen to be used as the cooling medium. An operators checklist and a detailed operational sequence to conduct constant strain rate tensile test are listed in Appendix B.

C. SAMPLE PREPARATION

The plate, once received at the Naval Postgraduate School was cut and machined into tensile test specimens. Two uniform gage-length specimens were made in accordance with



(a)



(b)

Figure 4. Experimental Test Equipment (a). Enviromental Chamber Mounted on Load Frame, with an hourglass Specimen Installed in Hydraulic Actuator Grips (b). MTS 810 Electronic Equipment Console

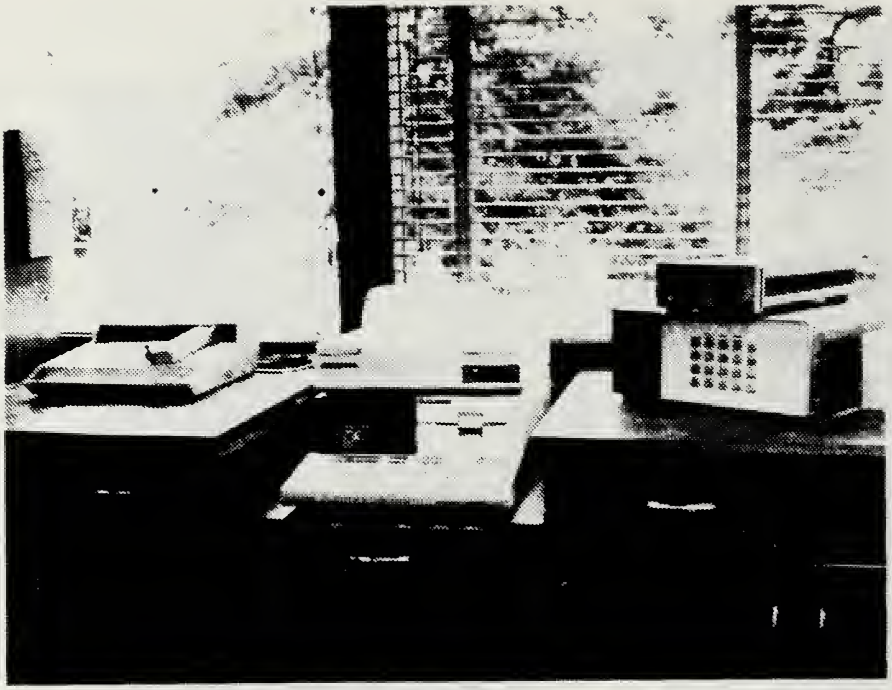
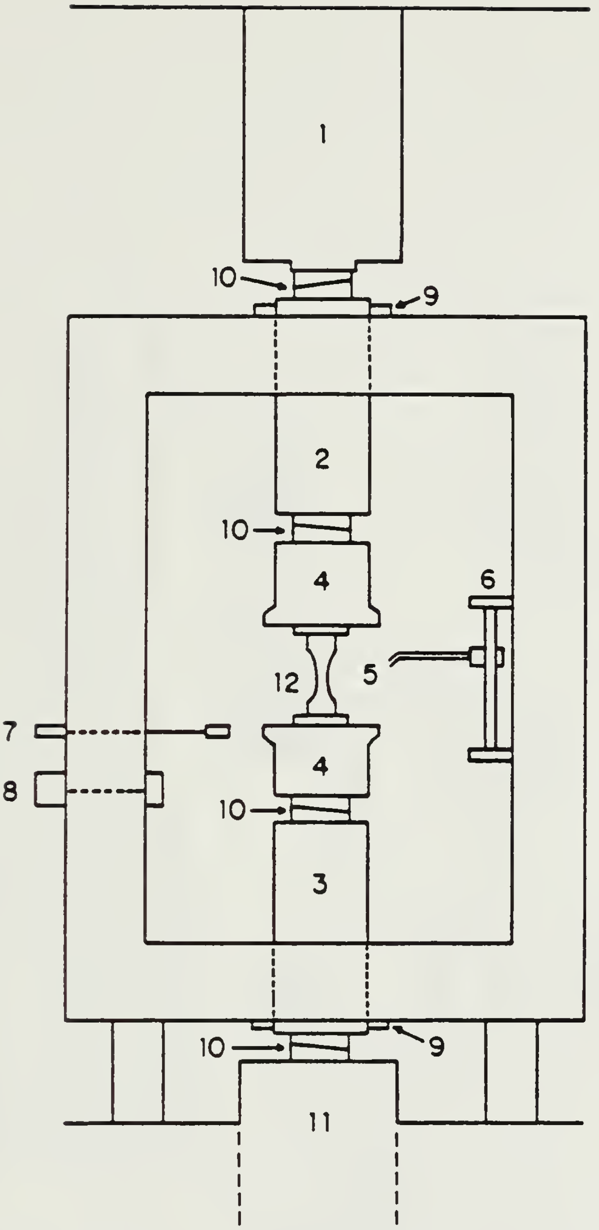


Figure 5. Hewlitt Packard 9826 Computer and Data Acquisition System

Figure 7. Twelve hourglass shaped specimens were made in accordance with Figure 8. The samples were cut from the plate parallel to the rolling (longitudinal) direction in all cases to ensure the consistency of the results. The hourglass specimen design was selected to ensure that fracture occured at the minimum specimen diameter where the strain is measured continously from test start to fracture by using a diametral extensometer. The data thus obtained could then be used to determine the appropriate constitutive equation for this material as a function of temperature.



1 - 25 KIP Load Cell
2 - Load Cell Extension
3 - Actuator Extension
4 - Thermal Hydraulic Grip
5 - Diametral Extensometer
6 - Extensometer Mount
7 - Extensometer Electrical Hook-up
8 - Thermal Couple Junction Box
9 - Seal
10 - Spiral Washers
11 - Actuator
12 - Hourglass Specimen

Figure 6. Enviromental Chamber, as Modified

NOTES: 1. All dimensions In inches.
2. Tolerances as per ASTM tensile specimen standards.
3. Specimen gage length to be paralled to plate as rolled direction.
4. Gage length shall be 32 rms.
5. Mark with applicable specimen number on both ends.

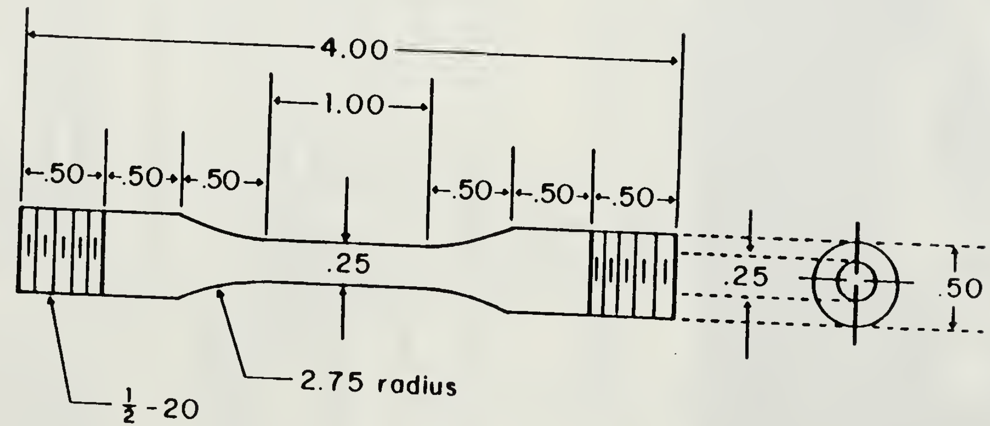


Figure 7. Uniform Gage-length Tensile Specimen Dimensions

NOTES:
1. All dimensions in inches.
2. Tolerances : As per ASTM tensile specimen standards.
3. Specimen gage length to be parallel to plate as rolled direction.
4. Reduced section area of specimen shall be polished in a manner paralled to specimen longitudinal axis to 32 rms.
5. Mark with applicable specimen number on both ends, vibrating type engraving tool is permissible.

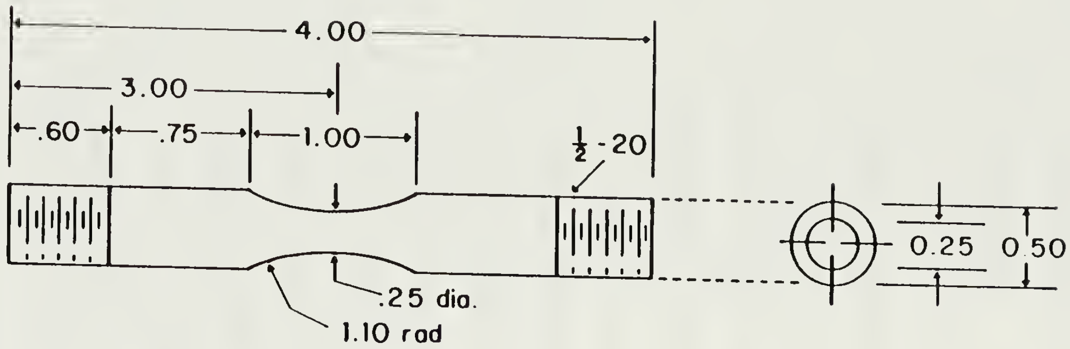


Figure 8. Hourglass Tensile Specimen Dimensions

D. COLLECTION, REDUCTION AND DISPLAY OF THE OUTPUT DATA

During a test, data is collected by the acquisition system using the program "JHCOLLECT", Appendix C lists this program. Upon completion of a tensile test the program allows the renaming of data files. The data files are generic in nature and are renamed after each test run with an appropriate specimen number, i.e. lod1, Dia1 etc. Appendix D lists the data reduction program "JHREDUCE". Running this program computes true strain/strain, log true stress/log true strain, corrected true stress/strain, plastic strain, log corrected true stress/true plastic strain and stores these values in arrays. The array names match the specimen numbers i.e. Stress1, Strain1. Appendix E lists the plotting program "JHPLOT". Running this program allows graphs of the array values stored by "JHCOLLECT" and "JHREDUCE". Appendix F lists the program "POWERFIT". Running this program plots the log corected true stress vs the log plastic true strain from the stored array values. Additionally, the strength coefficient, K, and strain hardening exponent, n, for the Hollomon power function are determined [Ref. 20:pp. 374-375]. Using the computed values of slope n and intercept log K a line is plotted between true plastic strain values of .001 and 1.0 . A correlation coefficient, R, for the power function is determined by the powerfit program using a least squares approximation. The correlation coefficient compares the fit between the log

corrected true stress versus log true plastic strain plot and the line generated using the power law coefficients determined.

E. TEMPERATURE MEASUREMENT AND CONTROL

Temperature measurement in this research was accomplished using chromel/alumel thermocouples. Chromel/alumel thermocouples are useful over the temperature range -200 to 1300 C. Their uncalibrated accuracy is + 3 C in the range 0 to 400 C [Ref. 27]. Many thermocouples normally used for high temperature monitoring show a decreasing temperature sensitivity with deceasing temperature. For chromel/alumel thermocouples below approximately -130 C the temperature/ voltage relation displays this decreasing sensitivity [Ref. 28]. The use of a known fixed temperature reference junction, near the measured temperature, is used to improve accuracy. Several thermocouples were tested in an ice water bath, zero degrees centigrade, and all indicated 0 C, this verified the calibration of the Newport temperature monitoring device. Additionally, the thermocouples were calibrated at -196 C using liquid nitrogen.

Two chromel/alumel thermocouples per test sample were used in the sub zero tensile tests conducted in this research. The samples were spot welded to the hourglass specimen, Figure 8, approximately 0.35 inches on each side of the specimen minimum diameter.

Low temperature tests were initially carried out using the MTS model 409 temperature controller. The controller activated a solenoid to either admit or stop the flow of liquid nitrogen to the enviromental chamber. The controller uses a thermocouple to compare sensed temperature with a manually adjustable setpoint. The coolant flow entered through the back of the chamber, by plastic tubing, and was then directed either on the specimen or the actuator grips. This arrangement was satisfactory for tests in which the lowest temperature achievable was desired. Once the specimen thermocouples were stable, at essentially liquid nitrogen temperature, the tensile tests were conducted while maintaining the flow of coolant to the chamber. This method of cooling the samples was not used for test temperatures between room temperature and liquid nitrogen temperature. In this range the on/off action of the solenoid/controller caused the temperature to vary as the coolant flow pulsed on and off. Additionally, the pulsing of coolant flow on the diametral extensometer produced an error signal from the extensometer which prevented starting the hydraulic system. This is a result of the difference in temperature of the extensometer and that of the liquid nitrogen. To conduct the tensile tests at temperatures below room temperature and above liquid nitrogen temperature the coolant flow system was modified. Figure 9, is a photograph of the inside of the enviromental chamber with the modified coolant system in

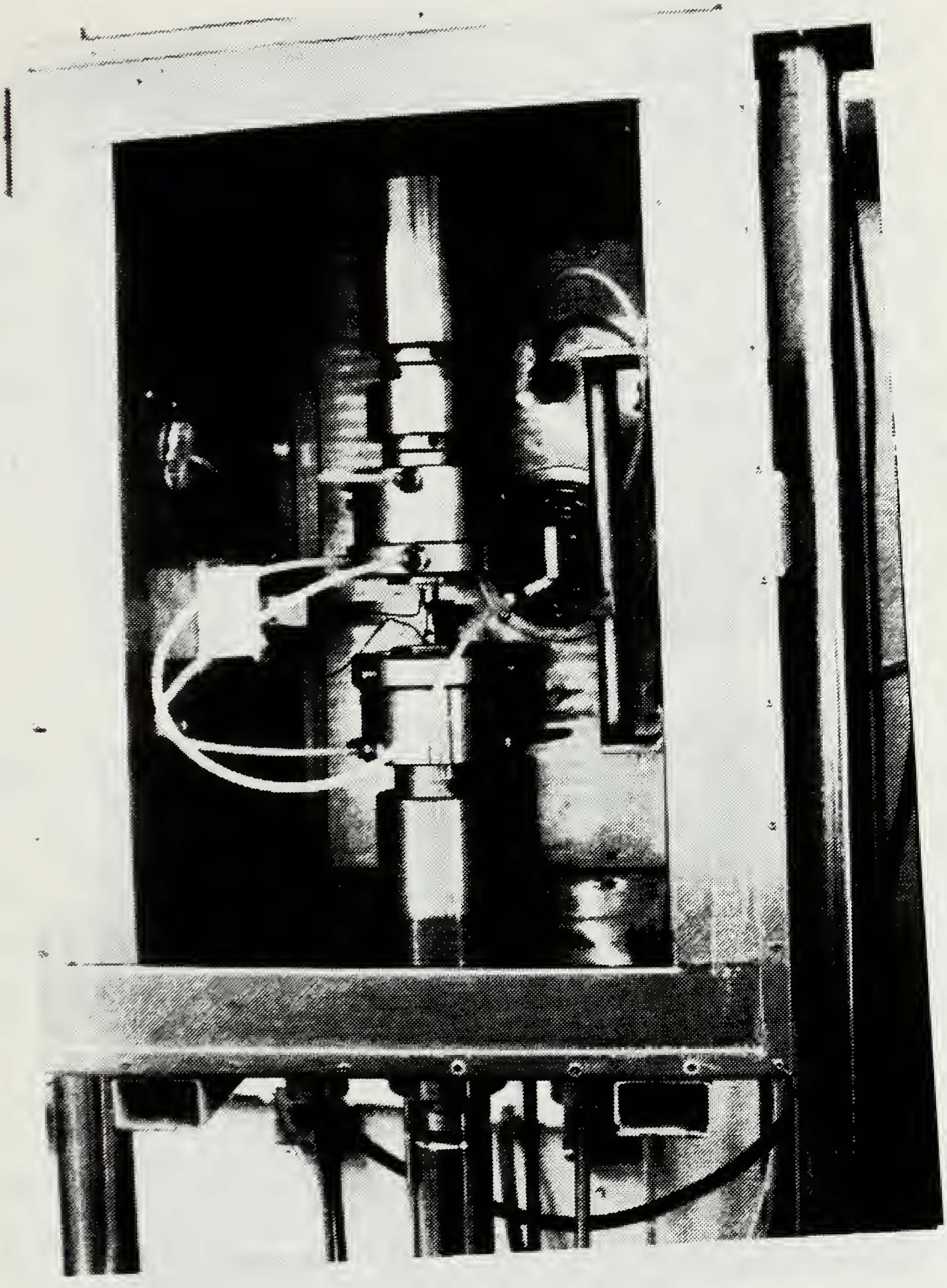


Figure 9. Enviromental Chamber Interior, Showing Modified Coolant System

place. Liquid nitrogen is directed by tubing to machined paths in the actuator grips. Thus, without coolant flow directly on the specimen, the sample is cooled by conduction from the grips to the desired test temperature. Once the temperature has stabalized, the flow of liquid nitrogen to the grips can be stopped and the grips provide a heat sink to maintain the sample at the desired test temperature. The thermocouples were monitored throughout each tensile test; and the average is reported as the test temperature.

F. MICROSCOPY

1. Optical Microscopy

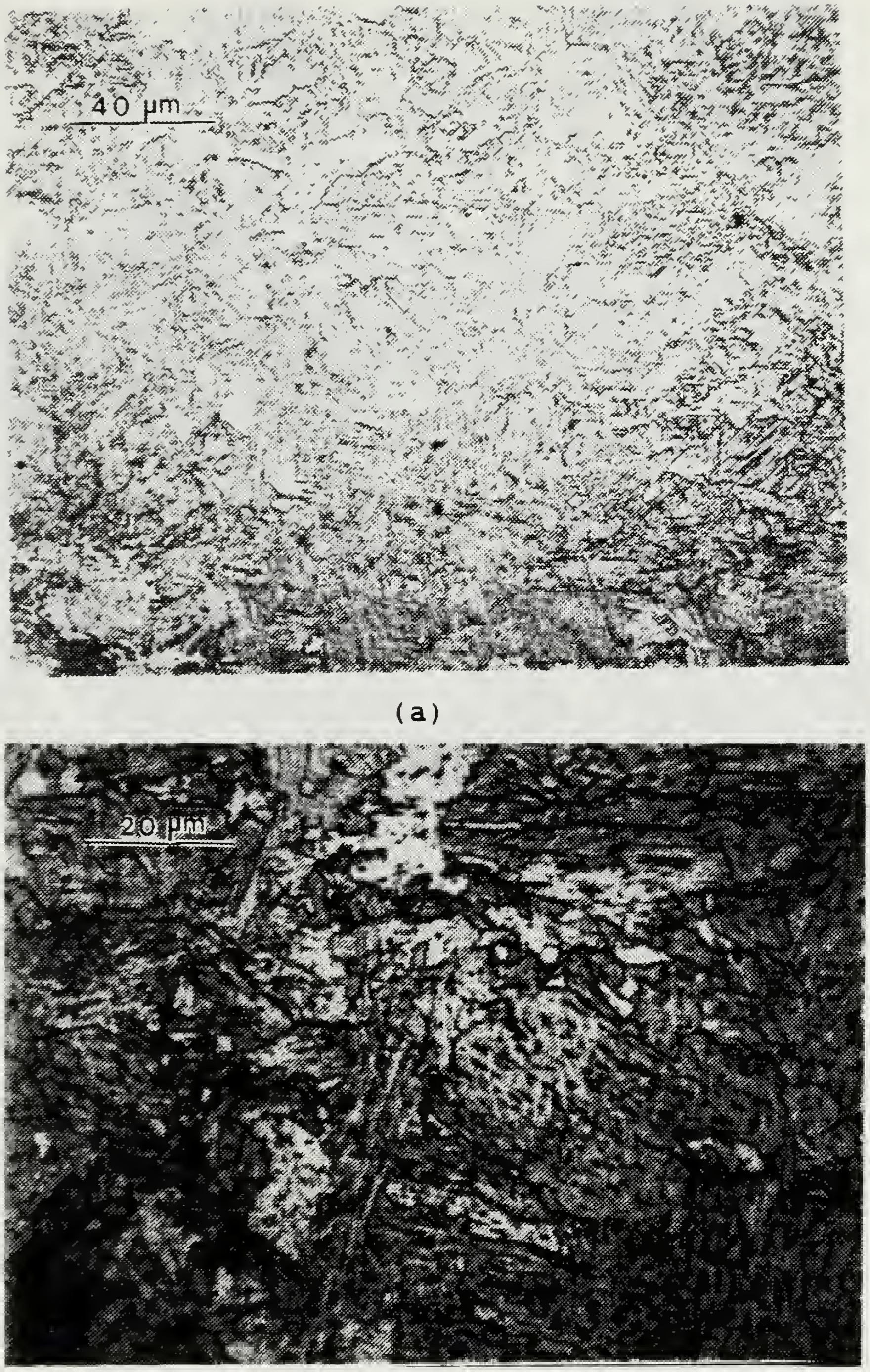
A polished and etched (2% nital) HSLA - 100 sample was photographed using a light microscope. Figure 10 (a) and Figure 10 (b) are representative of the microstructures observed. The microstructure is predominatly banitic and was uniform throughout the thickness of the plate, except for regions of increased grain size near the plate edges.

2. Scanning Electron Microscopy

The scanning electron microscope (SEM) was used to examine the HSLA - 100 tensile specimen fracture surfaces after testing. A discussion of the typical fracture surface and micrographs is presented in the results section.

3. Transmission Electron Microscopy

Figure 11 is a representative thin foil micrograph of the HSlA - 100 steel used in this research. The



(a)

(b)

Figure 10. Light Micrographs of HSLA - 100 Steel (a). Microstructure at 500X (b). Microstructure at 1000X

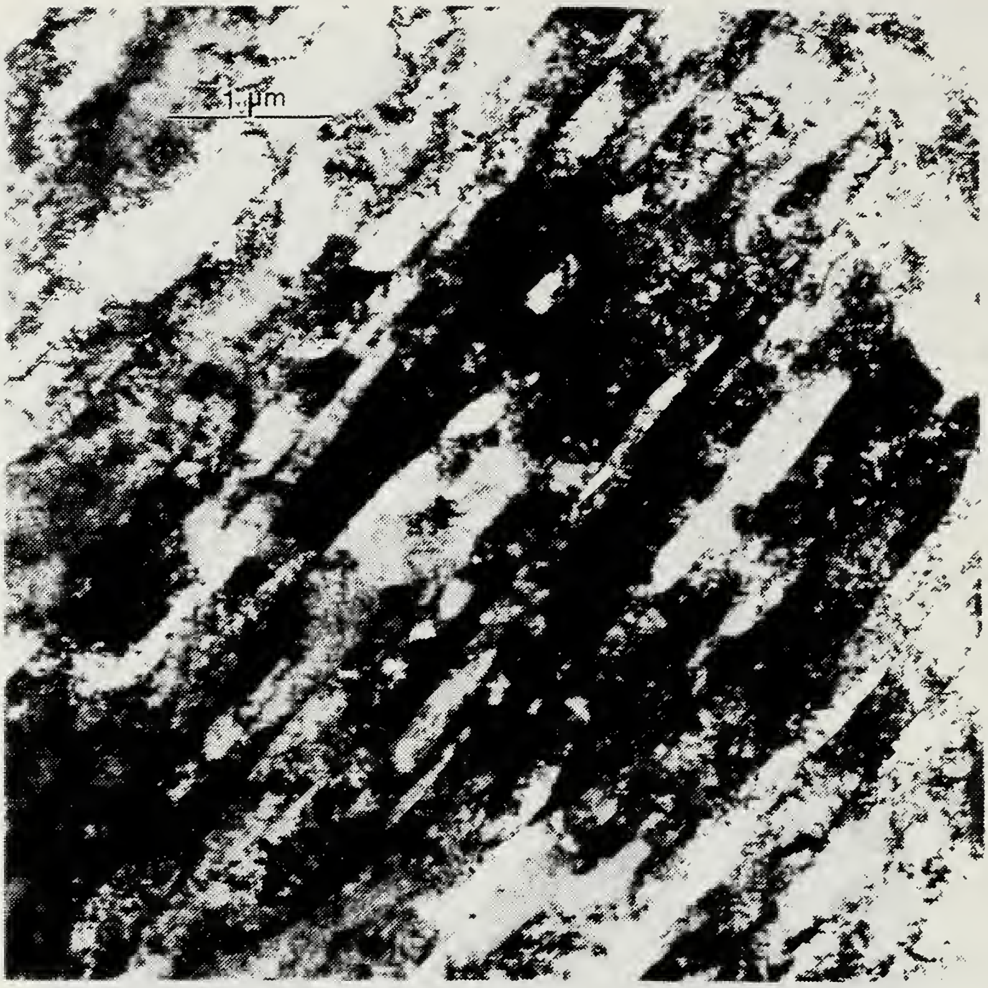


Figure 11. Thin Foil Transmission Electron Micrograph of HSLA - 100 Microstructure

microstructure is characterized by elongated parallel laths, less than 1 micron in width, containing a very high dislocation density. In addition, a uniform distribution of very fine niobium carbonitrides was also observed.

IV. RESULTS AND DISCUSSION

A. MEASUREMENT OF TRUE STRESS

Once a tensile test specimen begins to neck a triaxial stress state exists at the minimum cross-section, Figure 2. In order to obtain the true stress in the specimen a correction for this must be applied to the measured stress. Tegart discusses various expressions for the stress state in the neck but comments that the Bridgman correction most accurately estimates the degree of stress concentration [Ref. 19:pp. 21]. The Bridgman correction can be expressed as [Ref. 29]:

$$\sigma = \frac{\sigma_{av}}{(1 + 2\,R/r_n)[\ln(1 + r_n/2R)]}$$

where the measured average stress σ_{av} is reduced to a corrected value σ . R is the radius of curvature of the neck and r_n is the radius of the cross-section at the neck.

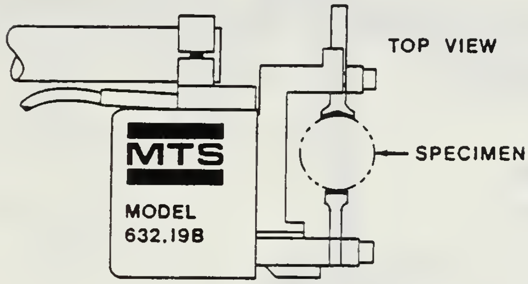
The initial radius of curvature of the hourglass section of the specimen used in this study is 1.1 in.; this results in an initial correction of $0.972\,\sigma_{av}$. The objective of this research was to measure true stress and true strain from the onset of loading to the point of fracture. Thus this initial correction has been applied to the true stress up to the onset of necking. Once a test was completed the final radius of curvature was measured by first fitting the specimen

back together and magnifying the necked region with an overhead projector. Then comparing the fit of various circular templates to the projected image produced the final radius of curvature (when divided by the magnification factor). This value along with the measured final cross-section radius allowed determination of a final correction factor for each test specimen. In order to gradually change the magnitude of the Bridgman correction from the onset of necking to fracture, a linear relation was developed between the value at the onset of necking and the fracture point for each specimen. This relation was then applied to the measured true stress values after the maximum load was reached. The justification for using a linearly changing correction factor derived from the fact that the tests were conducted with a constant diametral displacement rate. The computation of the linear relation for the correction factor and its application to individual points is accomplished by the data reduction program, Appendix D.

B. MEASUREMENT OF TRUE STRAIN

The true strain was determined using an MTS model 632.19B-21 diametral extensometer. Figure 12 shows a typical series 632.19B adjustable diametral extensometer and lists the operating characteristics based on specific model number. The extensometer contacts, shown more clearly in Figures 13 and 14, were not capable of following the

MODEL 632.19B ADJUSTABLE
DIAMETRAL EXTENSOMETER



Model:-	632.19B-20	632.19B-21	632.19B-23
Gage Diameter Adjustment	3,6 mm to 13 mm 0.140 in. to 0.520 in.	3,6 mm to 13 mm 0.140 in. to 0.520 in.	3,6 mm to 13 mm 0.140 in. to 0.520 in.
Maximum Range (Diametral)	±1,0 mm ±0.040 in.	±1,0 mm ±0.040 in.	±1,0 mm ±0.040 in.
Linearity**	0.25% of range	0.25% of range	0.25% of range
Maximum Hysteresis	0.3% of range	0.3% of range	0.3% of range
Temperature Range	-115°F to +250°F	-450°F to +150°F	-450°F to +350°F
Immersibility***	Yes	Yes	Yes
Max Operating Freq with Negligible Distortion	100 Hz	100 Hz	100 Hz
Effective Inertial Mass	45 grams	45 grams	63 grams
Approx Clamp Force on Specimen	250 grams min 325 grams max	250 grams min 325 grams max	250 grams min 325 grams max
Recommended Calibrated Ranges for 10V full scale output from MTS Transducer Conditioner****	±0.040 in./±1,0 mm ±0.020 in./±0,5 mm ±0.008 in./±0,2 mm ±0.004 in./±0,1 mm	±0.040 in./±1,0 mm ±0.020 in./±0,5 mm ±0.008 in./±0,2 mm ±0.004 in./±0,1 mm	±0.040 in./±1,0 mm ±0.020 in./±0,5 mm ±0.008 in./±0,2 mm ±0.004 in./±0,1 mm

*All models include case, instruction manual, and mating connector (Amphenol 165-14).

**When calibrating over a range from tension to compression, linearity is somewhat degraded; however, this is electronically compensated to the stated value by the recommended MTS Transducer Conditioner modules.

***Immersible in most fluids used for specimen heating and cooling, including alcohol, acetone and silicone fluids.

****Recommended Transducer Conditioners: 440.21, 425.41 (option B), 406 (option A). Other conditioners may be used (maximum excitation is 12v, output is approximately 3mv/v).

Figure 12. Model 632.19B Diametral Extensometer and a Table of Specific Model Operating Characteristics

diametral displacement once necking produced a radius of curvature below .5 inches. The contacts were modified to allow the measurement of strain up to the minimum radius of the neck which preceeded fracture. Figure 15 is a photograph of the extensometer contacts after modification. The limited range of accurate unmodified extensometer travel is

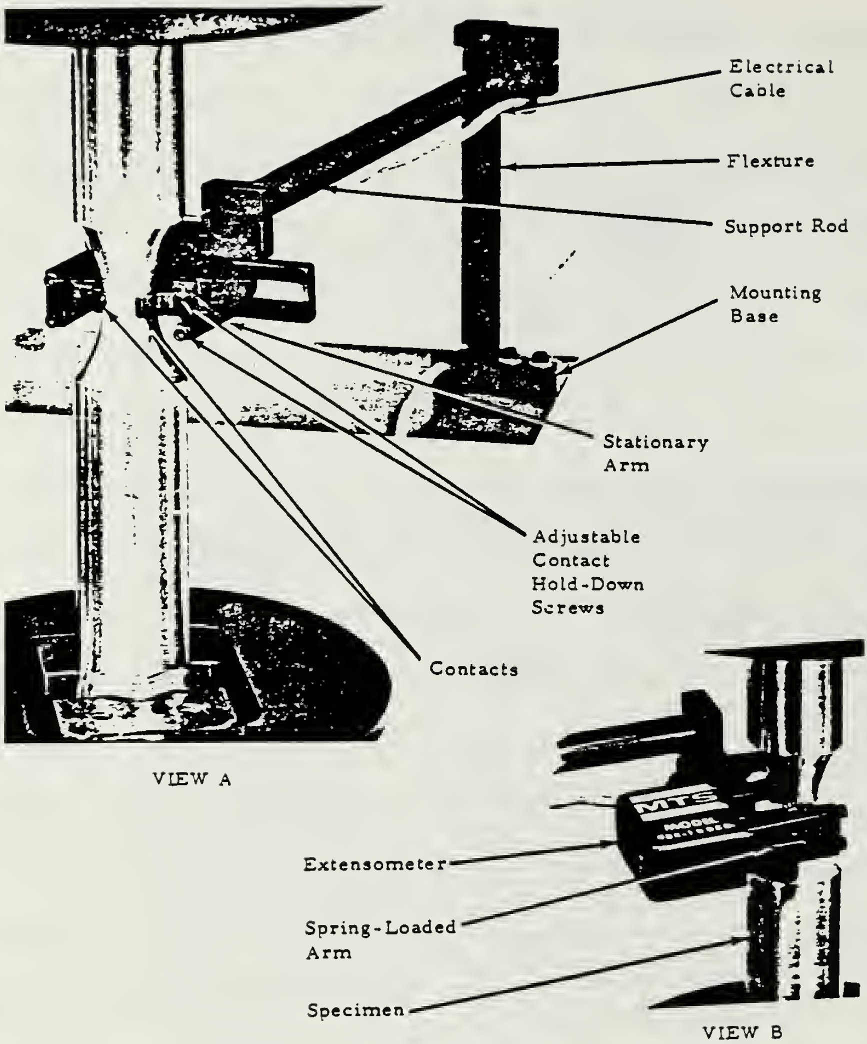


Figure 13. Typical Series 632 Adjustable Diametral Extensometer - Attatchment to Specimen

reflected in Figure 16, the load vs. diametral displacement curve for hourglass specimen number 4. Figure 17, the load displacement curve for hourglass specimen number 5, illustrates the improved range of measuring diametral displacement once the extensometer was modified.

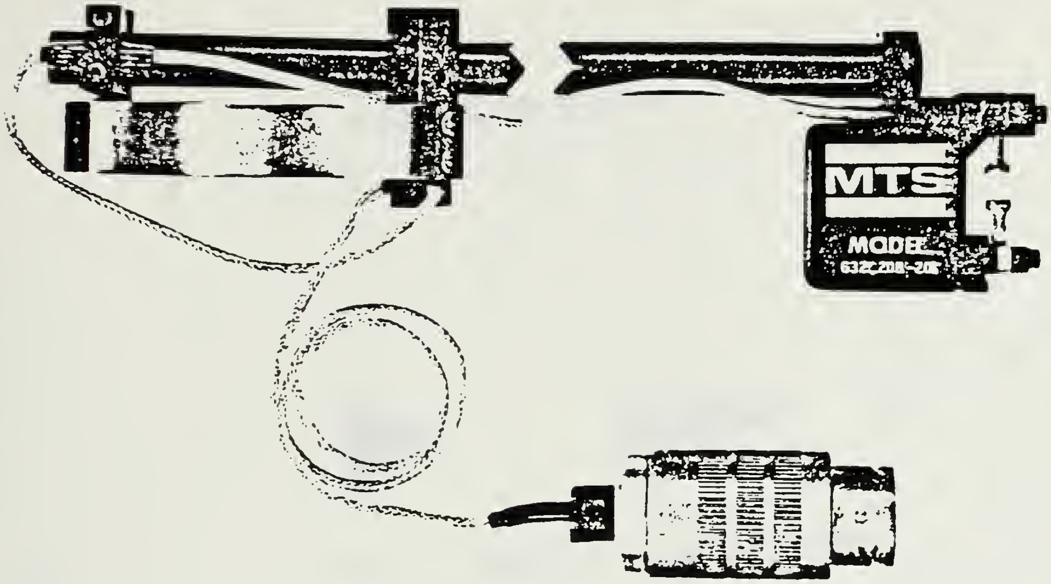


Figure 14. MTS Diametral Extensometer with Mounting Assembly and Electrical Connection

C. DETERMINATION OF THE MODULUS OF ELASTICITY

The value of the modulus of elasticity or Young's modulus for the HSLA - 100 steel tested in this research was determined experimentally. The test of hourglass specimen number 4, Figure 16, indicated yielding occured for loads above approximately 5.5 Kips. A uniform gage-length specimen equiped with an axial extensometer was loaded to 4 Kips in load control at a rate of 4×10^{-3} Kip/sec. The specimen was loaded to 4 Kips then returned to zero load at the same rate. This was done twice and the value of Young's modulus determined by the slope of the stress - strain curve generated by an X - Y recorder. The average value of Young's modulus for the two tests is 2.414×10^{6} psi. This value was

Figure 15. Model 632.19B-21 Diametral Extensometer Contacts (Unmodified and Modified)

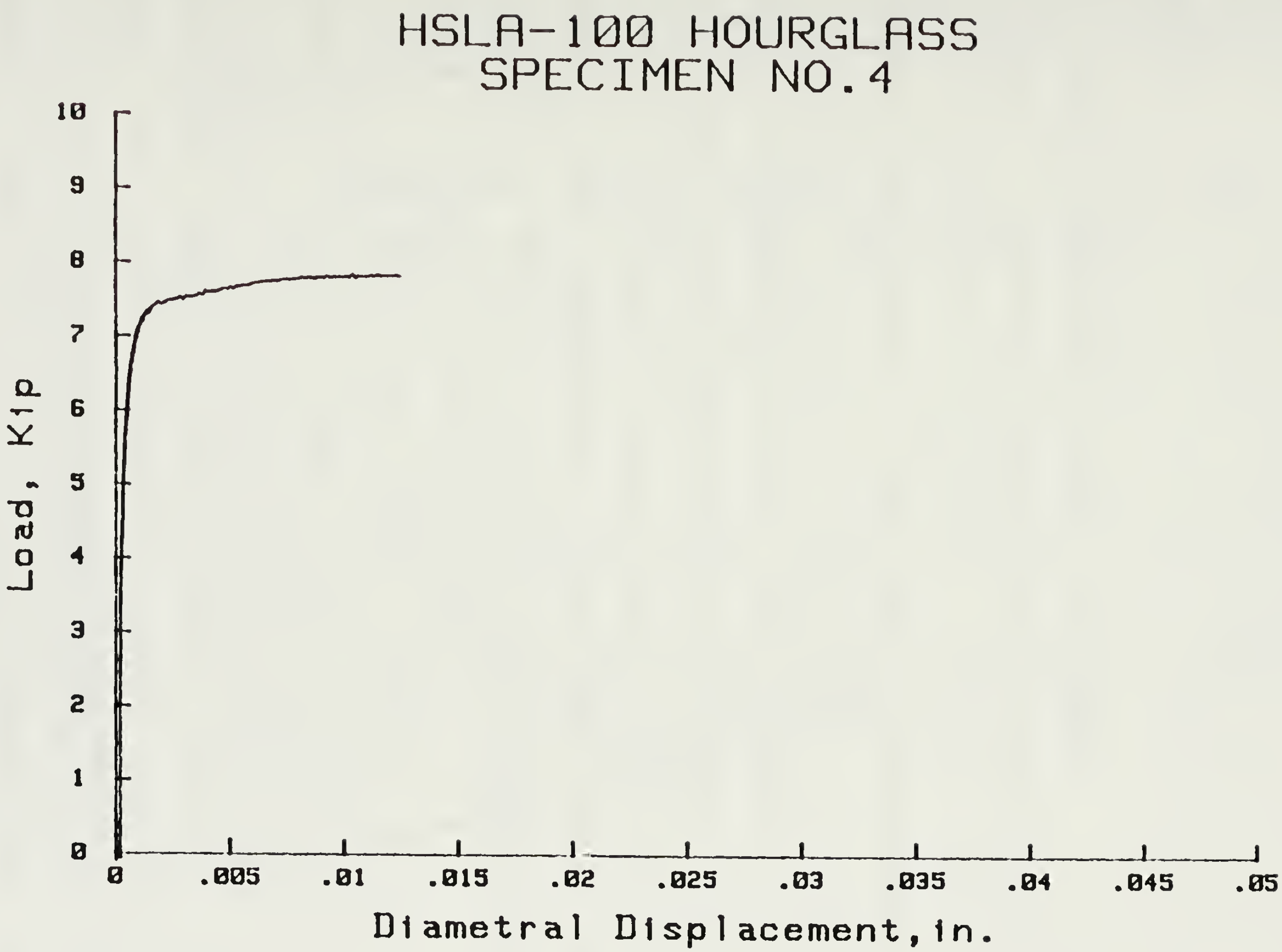


Figure 16. Load - Diametral Displacement Curve for Hourglass Specimen No. 4, Tested at Room Temperature.

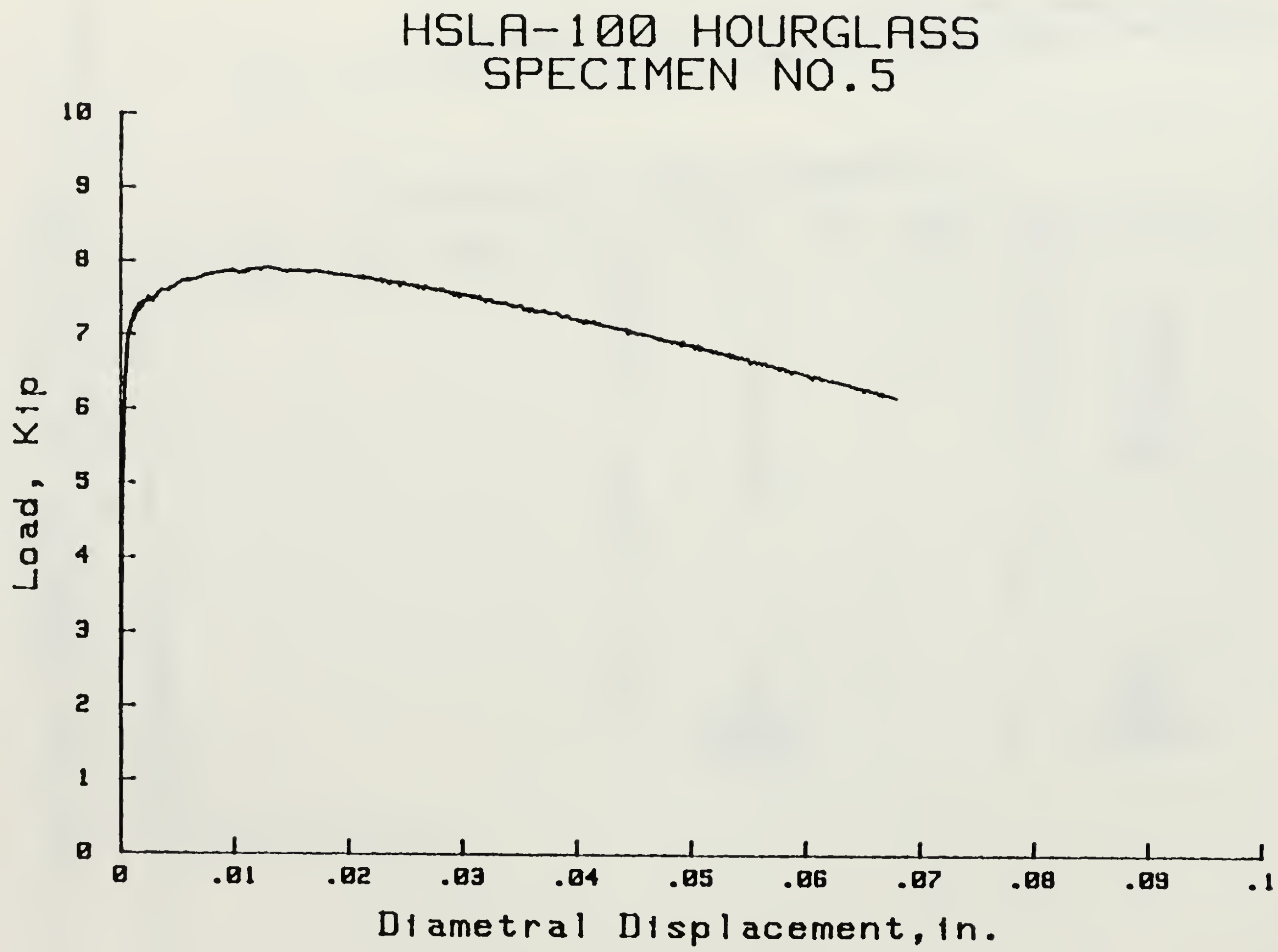


Figure 17. Load - Diametral Displacement Curve for Hourglass Specimen No. 5, Tested at Room Temperature

then used along with the corrected true stress in the determination of the true plastic strain, as follows:

$$\epsilon_p = \epsilon_t - \sigma/E$$

where ϵ_p is the true plastic strain, ϵ_t the total true strain, σ the corrected true stress and E is Young's modulus.

D. TENSILE PROPERTIES OF HSLA - 100 STEEL

Table II summarizes the mechanical properties for HSLA - 100 resulting from this research. The test temperature for hourglass specimen no. 6 was taken as the average of the test start and test complete temperatures. There was a 36 C change in temperature from test start to specimen failure as the coolant supply exhausted prior to starting the test and prior to the actuator grips/extensions equilibrating at the desired test temperature. In all other tests the test temperature, taken as the start/finish average, varied less than + 10 C from the start to finish.

In comparing the results reported by the plate manufacturer listed in Table II with those obtained in this study Table I, an obvious difference exists. The uniform gage-length samples from this study exhibited comparable values for percent reduction in area (% R/A) and ultimate tensile strengths (UTS) to those reported by the supplier. However, the .2% offset yield strength values are much

higher and the % elongation is much lower than reported by the supplier. The unexpectedly high yield strength results, of the room temperature tensile tests were reported to the project liaison at David Taylor Research and Development

TABLE II

STRENGTH PROPERTIES OF HSLA - 100 PLATE # 5644-16B (AS DETERMINED IN THIS RESEARCH) - HOURGLASS SPECIMEN

No.	Average Test Temperature (deg C)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 1 inch (%)	Reduction in Area (%)
1	21	a	a	N/A	63.0
2	21	127.0	156.9	N/A	b
3	20	a	a	N/A	62.7
4	20	126.0	156.7	N/A	59.6
5	24	130.8	156.1	N/A	63.7
6	-109	159.0	177.2	N/A	*48.8
7	-176	184.2	201.2	N/A	27.0
8	-196	a	a	N/A	27.0
9	-72	146.8	164.1	N/A	62.3
10	-27	137.2	159.3	N/A	64.7
11	-150	167.7	184.2	N/A	*54.5
12	-129	156.7	177.0	N/A	*55.9
	UNIFORM GAGE-LENGTH SPECIMEN				
1	23	132.7	142.6	12.3	68.6
2	22	130.4	142.6	16.4	68.6

a - no data collected.
b - specimen not tested to the point of fracture.
* - specimen didnot fail at the minimum diameter. The % R/A in the table is based on the specimen minimum diameter and is therefore a conservative (low) value.

Center, Mr. M. Vassilaros. Subsequent conversation with Mr. Vassilaros revealed that the plate received at the Naval Postgraduate School had not been heat treated properly and

that yield strengths above those in the interim HSLA - 100 specification should be expected.

In addition to the load versus diametral displacement curves, as shown in Figures 16 and 17, the reduction and plotting programs, Appendices D and E respectively, allow other useful curves to be generated. The next several figures will provide a sample of the various plots and serve to compare the results at room temperature to a test at - 176 C.

The true stress - true strain curves at room temperature and -176 C are shown in Figures 18 and 19 respectively. Note the marked increase in true stress and corresponding decrease in ductility in the -176 C temperature test. As expected, the strength is higher and ductility lower at -176 C than at room temperature. Figure 20, applies the linearly varying Bridgman corrected true stress to the results shown in Figure 18. The maximum correction to the true stress for the triaxial stresses in the necked region of this sample is 0.955. The maximum travel (0.072) of the diametral extensometer was too small to follow the deformation process to the fracture point, the fracture point is plotted as an asterisk. The decrease in ductility at low temperatures, Figure 21, allowed the extensometer to follow the deformation process to the fracture point. The log true stress-log true strain curves for room temperature and -176 C are shown in Figures 22 and 23. When the true stress is

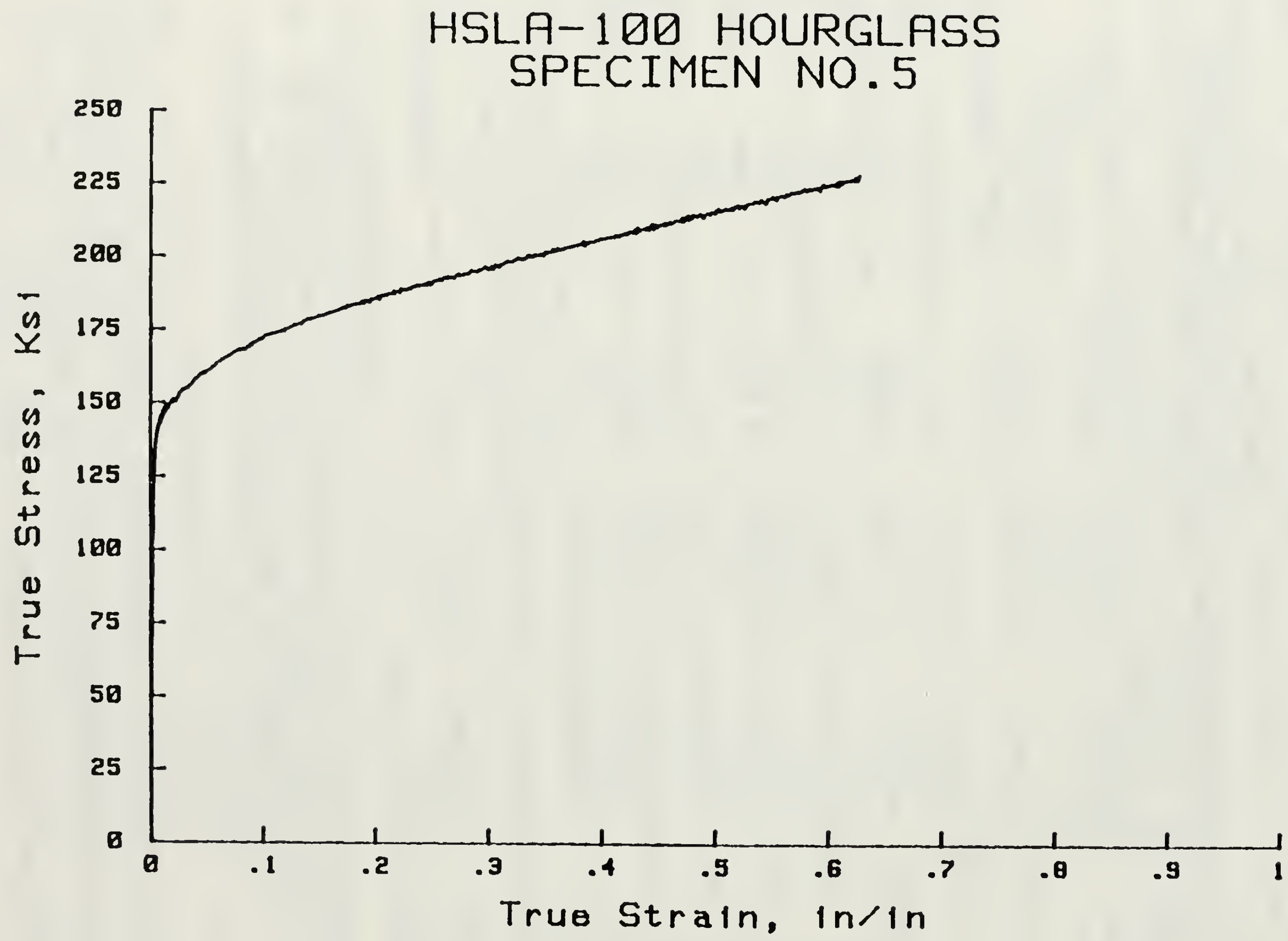


Figure 18. True Stress - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature

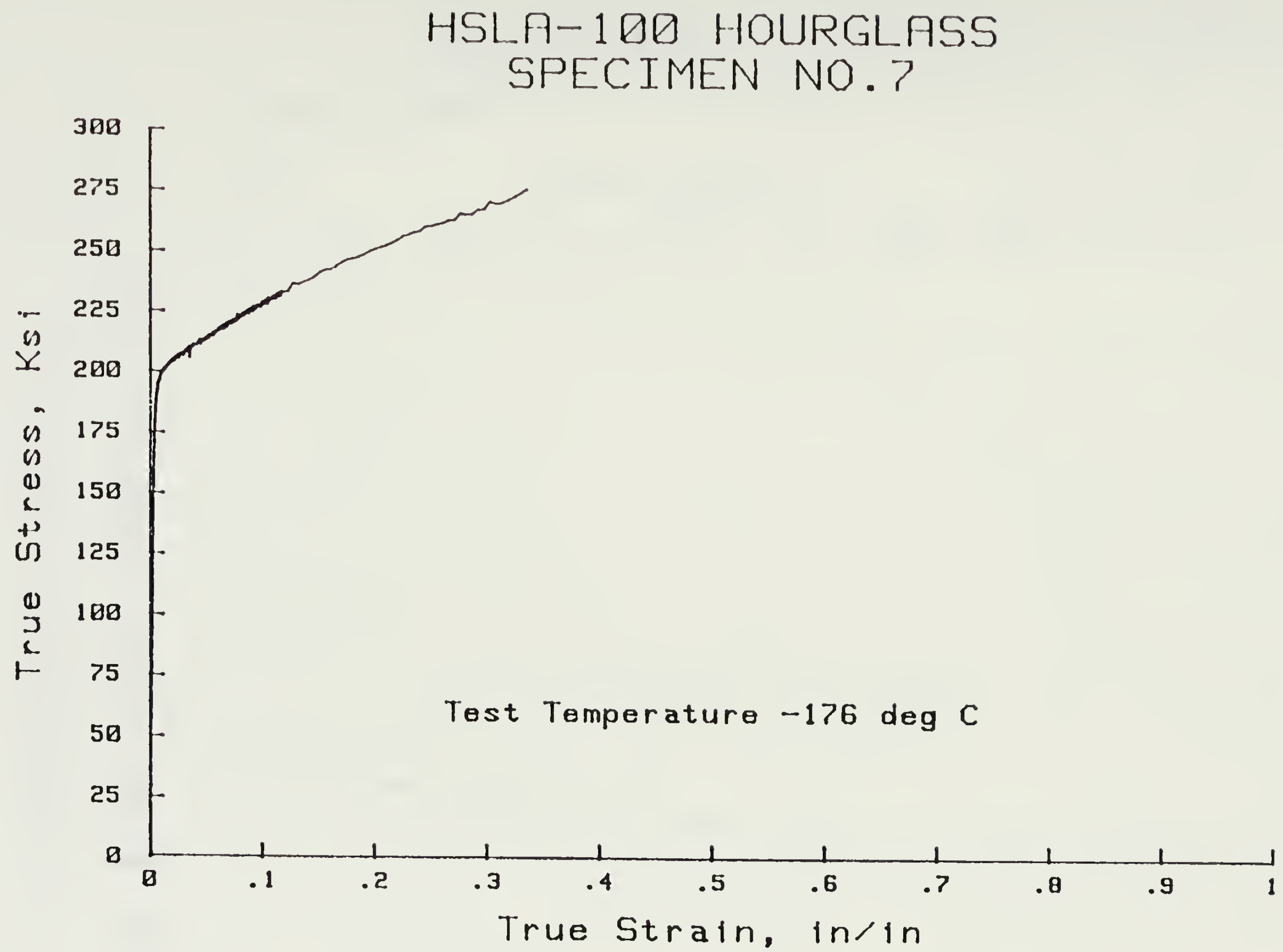


Figure 19. True Stress - True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C

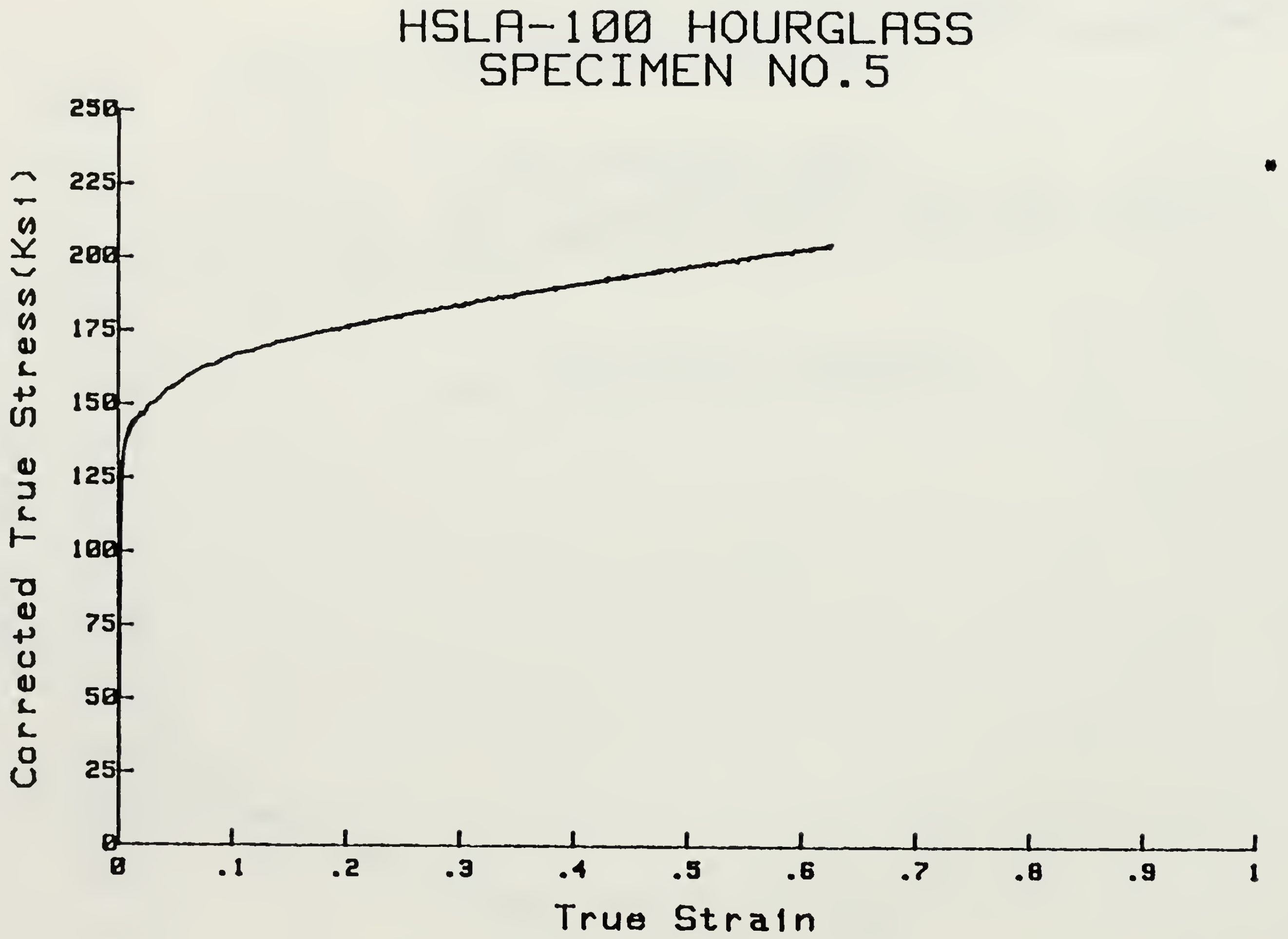


Figure 20. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, * Indicates Fracture Point

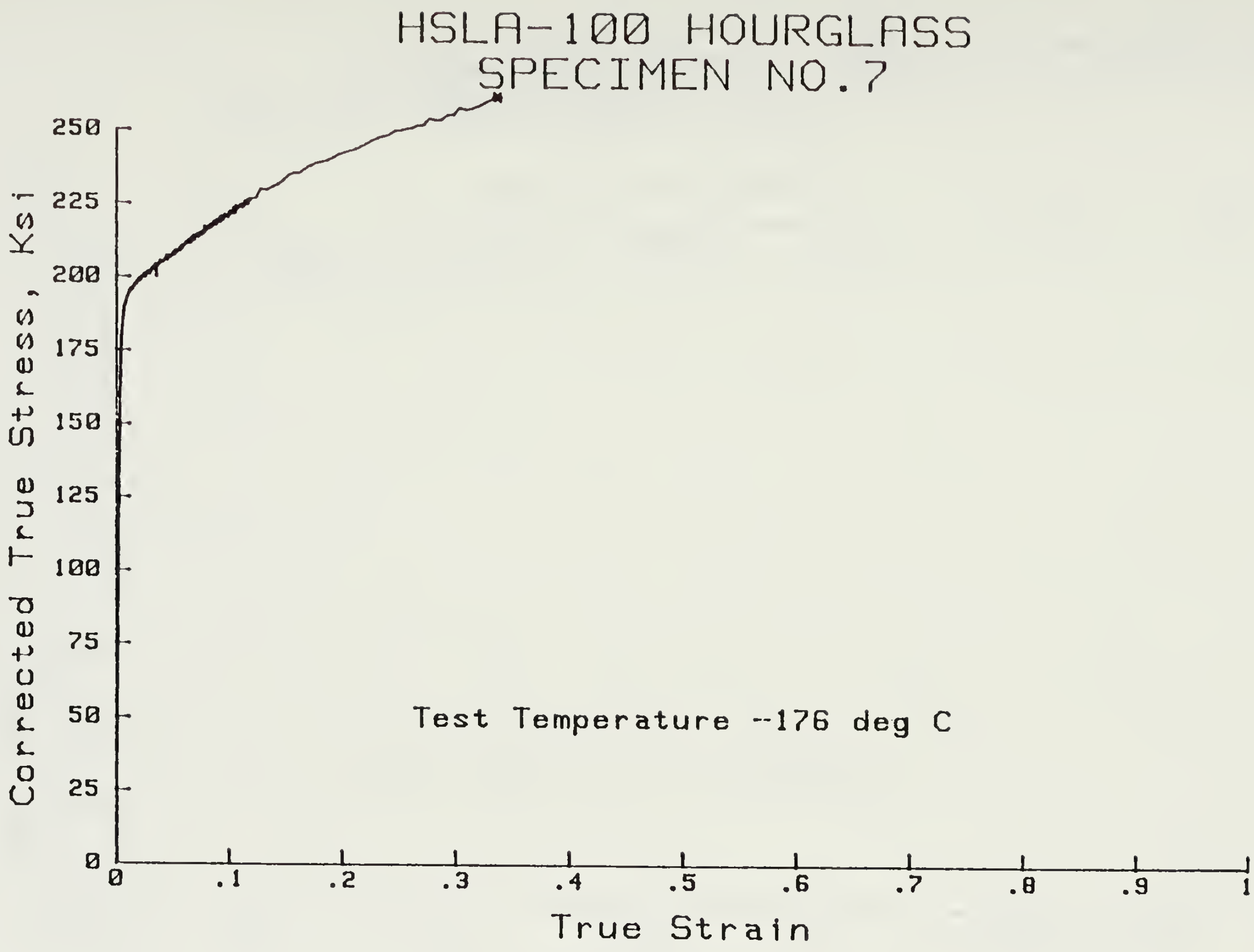


Figure 21. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point

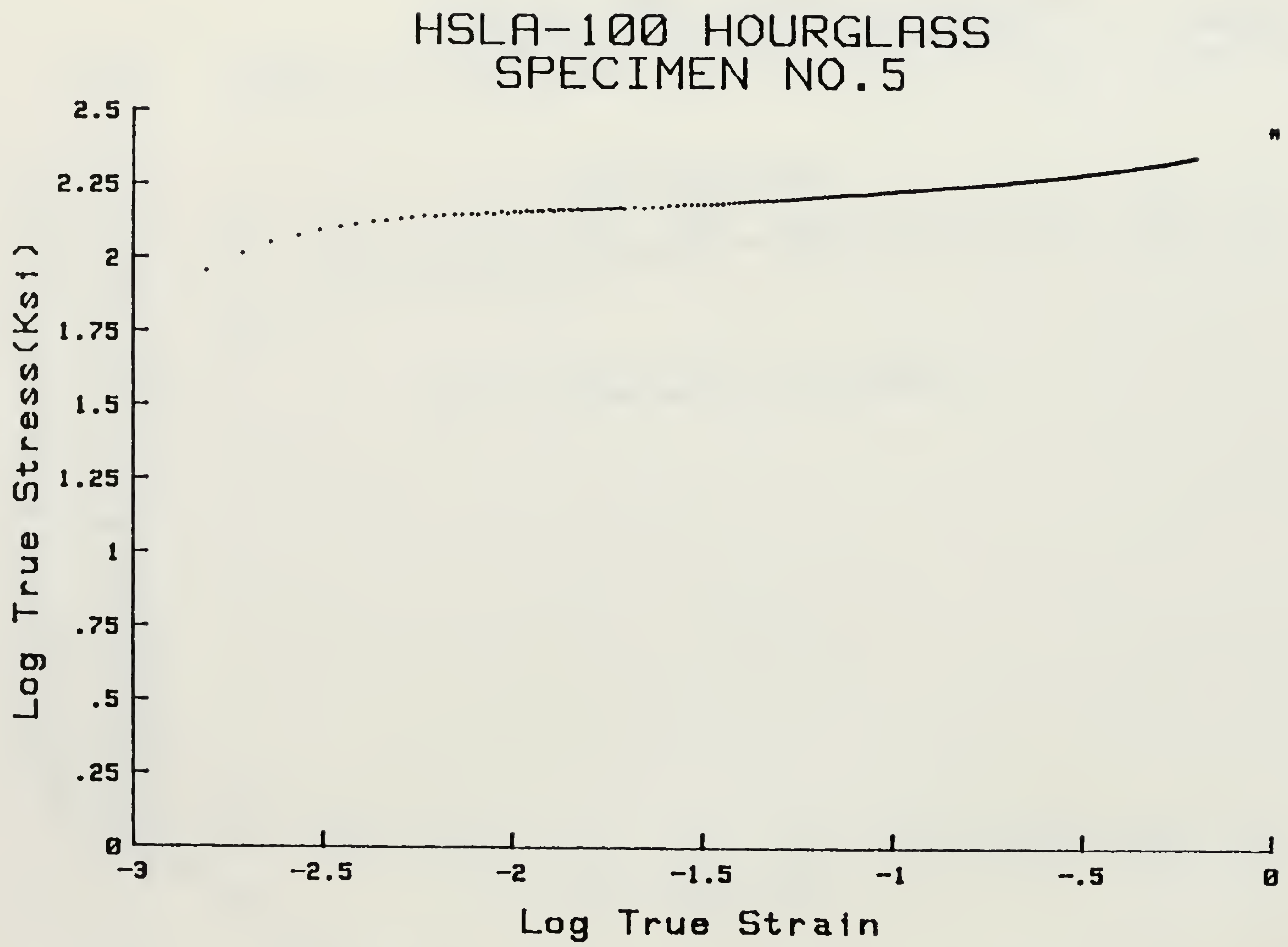


Figure 22. Log True Stress - Log True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, * Indicates Fracture Point

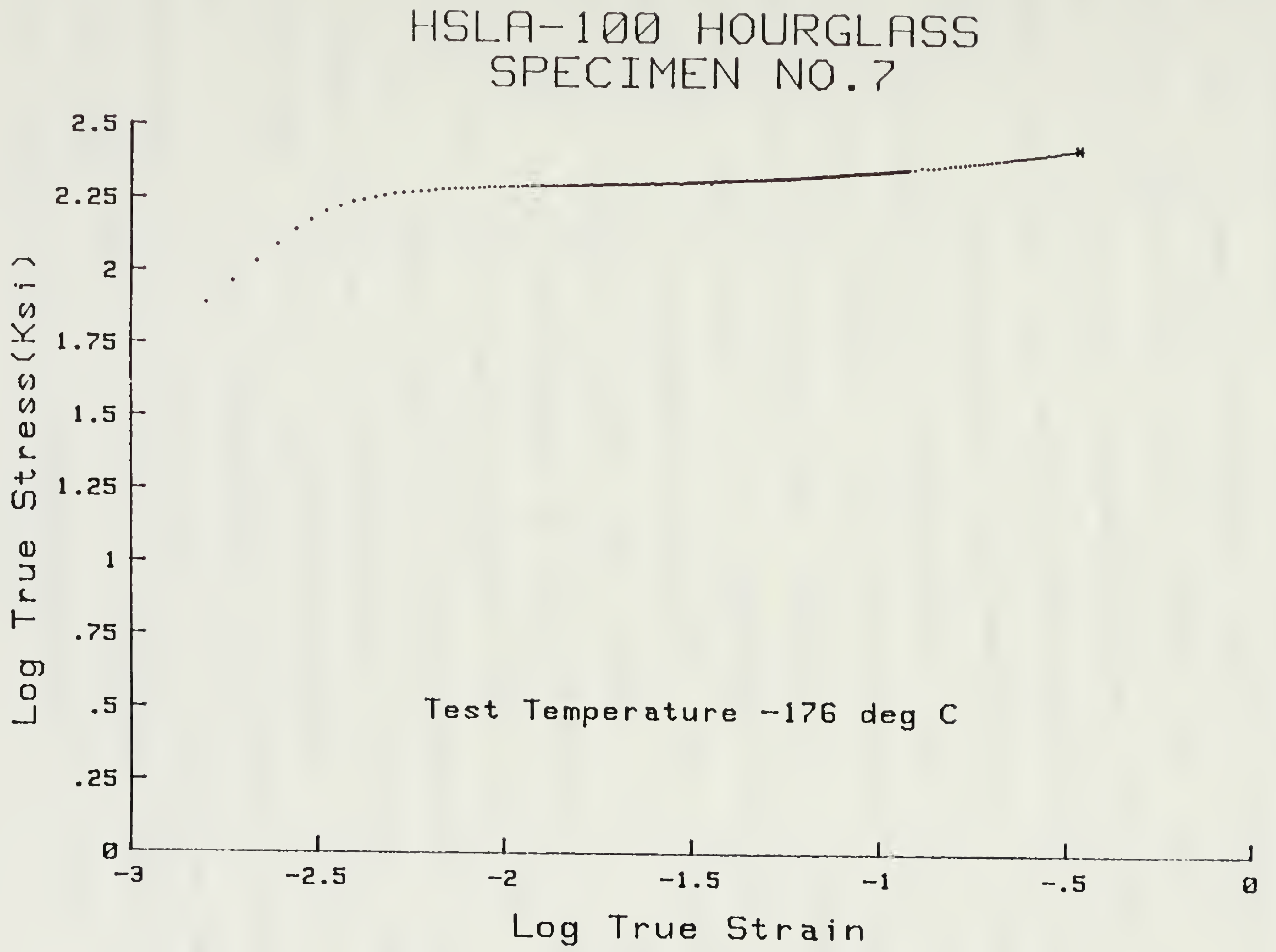


Figure 23. Log True Stress - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point

corrected for initial specimen geometry and the triaxiality associated with necking the resulting curves, Figures 24 and 25, reflect a lowering of the log true stress values. The reduction in corrected log true stress values over the uncorrected values increases with increasing strain due to the decreasing radius of curvature in the necked area. The log true strain values in Figures 22 through 25 are total true strain. By subtracting the elastic strain from the total true strain an approximately linear true stress - true plastic strain results when plotted logarithmically, Figures 26 and 27; the Holloman power function appears to closely describe the stress - strain behavior of this material.

Figure 28 presents the yield strength of HSLA - 100 as a function of temperature. The rapidly increasing strength with decreasing temperature is a result of the increasing Peierls force with decreasing temperature for this body centered cubic steel. The percent reduction in area undergoes a rapid decrease at temperatures below -150 C, Figure 29. The three results between -100 C and -150 C represent the minimum percent reduction in areas, since the specimens actually failed outside the minimum diameter. These results indicate that HSLA - 100 steel experiences little loss in ductility at temperatures above -150 C. The fact that specimens 6, 11, and 12 failed outside the minimum diameter is most remarkable. In all three cases significant necking, based on % R/A, preceeded specimen failure. The

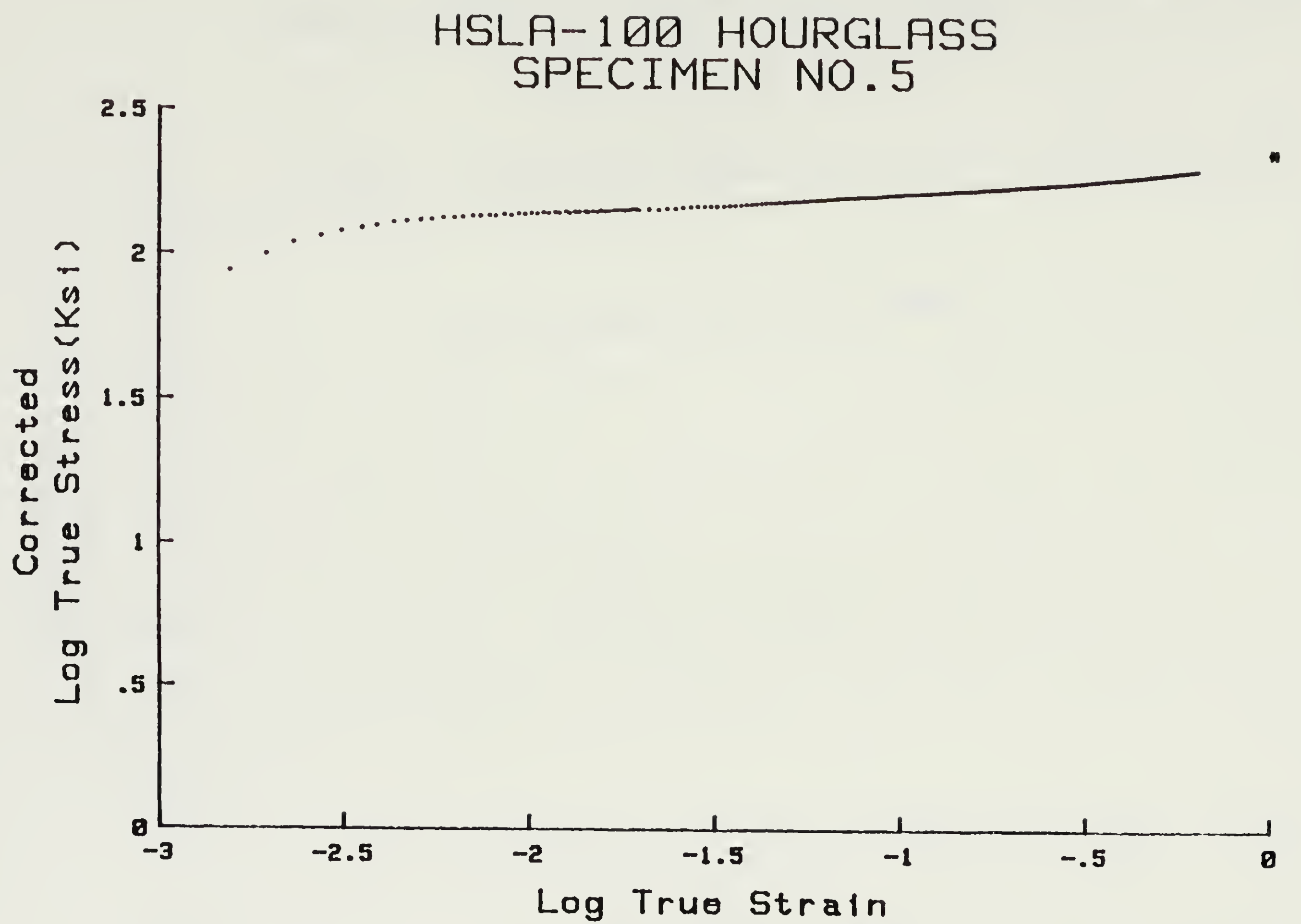


Figure 24. Log True Stress (Corrected for Necking) - Log True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, * Indicates Fracture Point

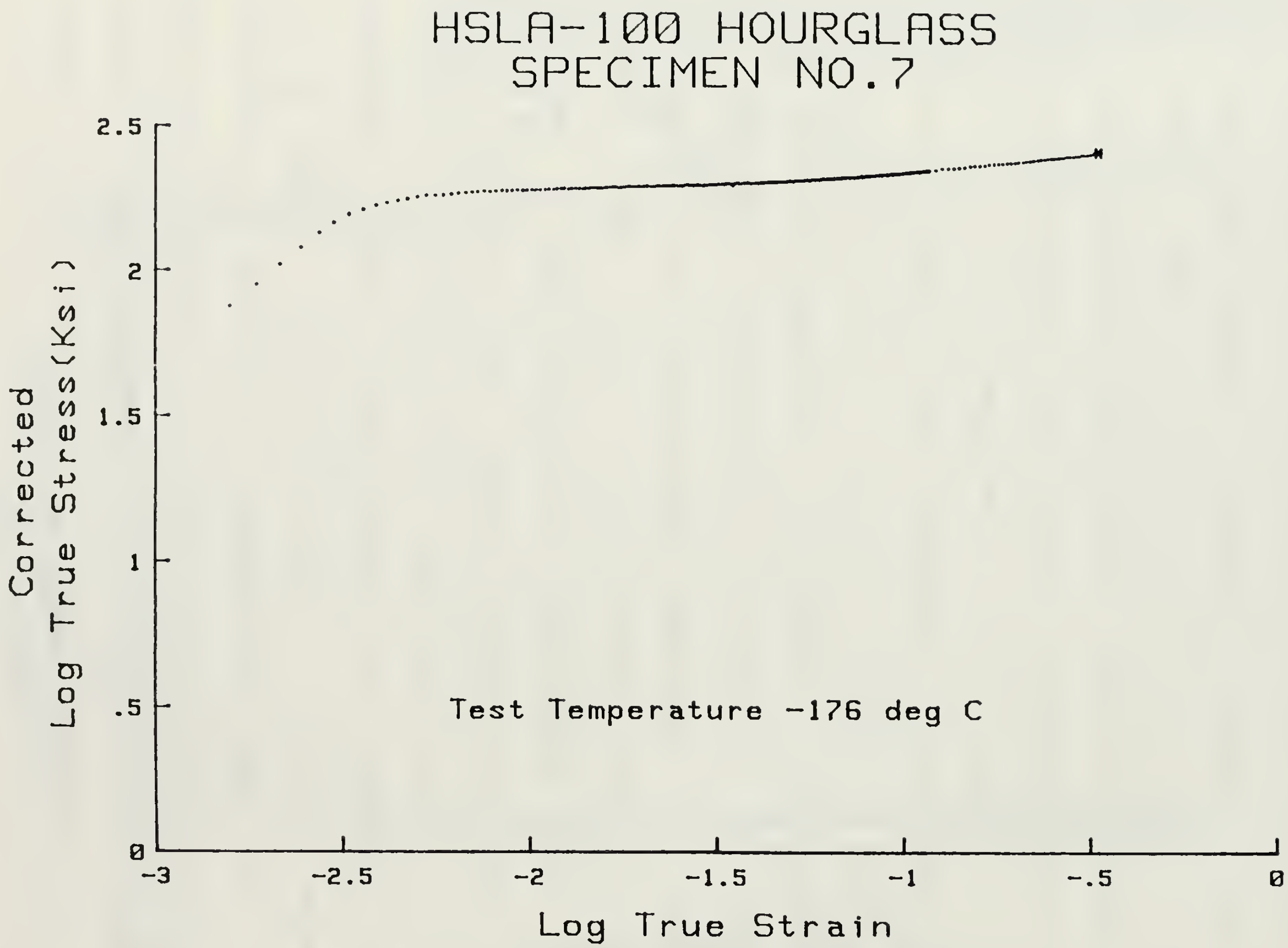


Figure 25. Log True Stress (Corrected for Necking) - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point

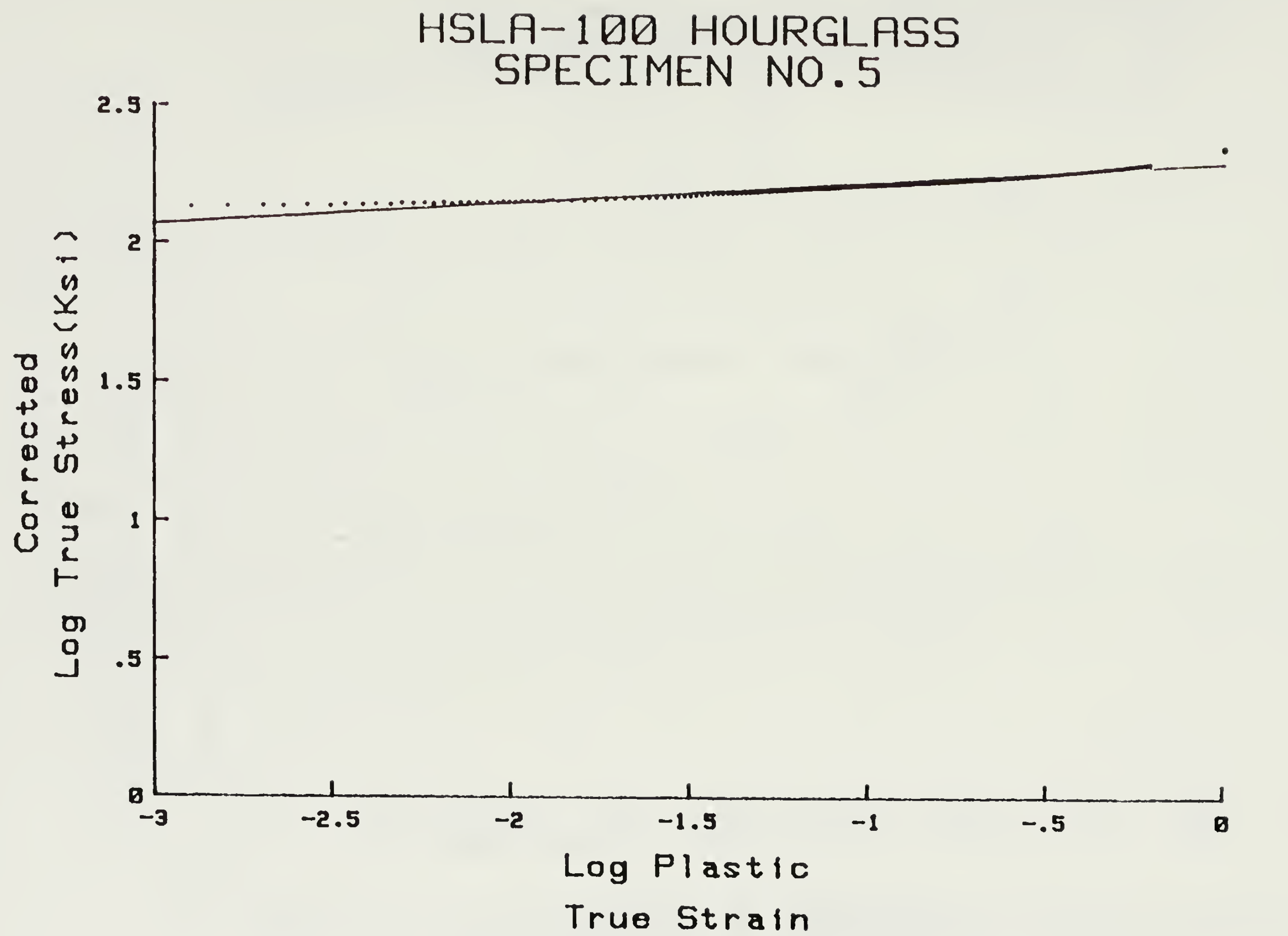


Figure 26. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, * Indicates Fracture Point

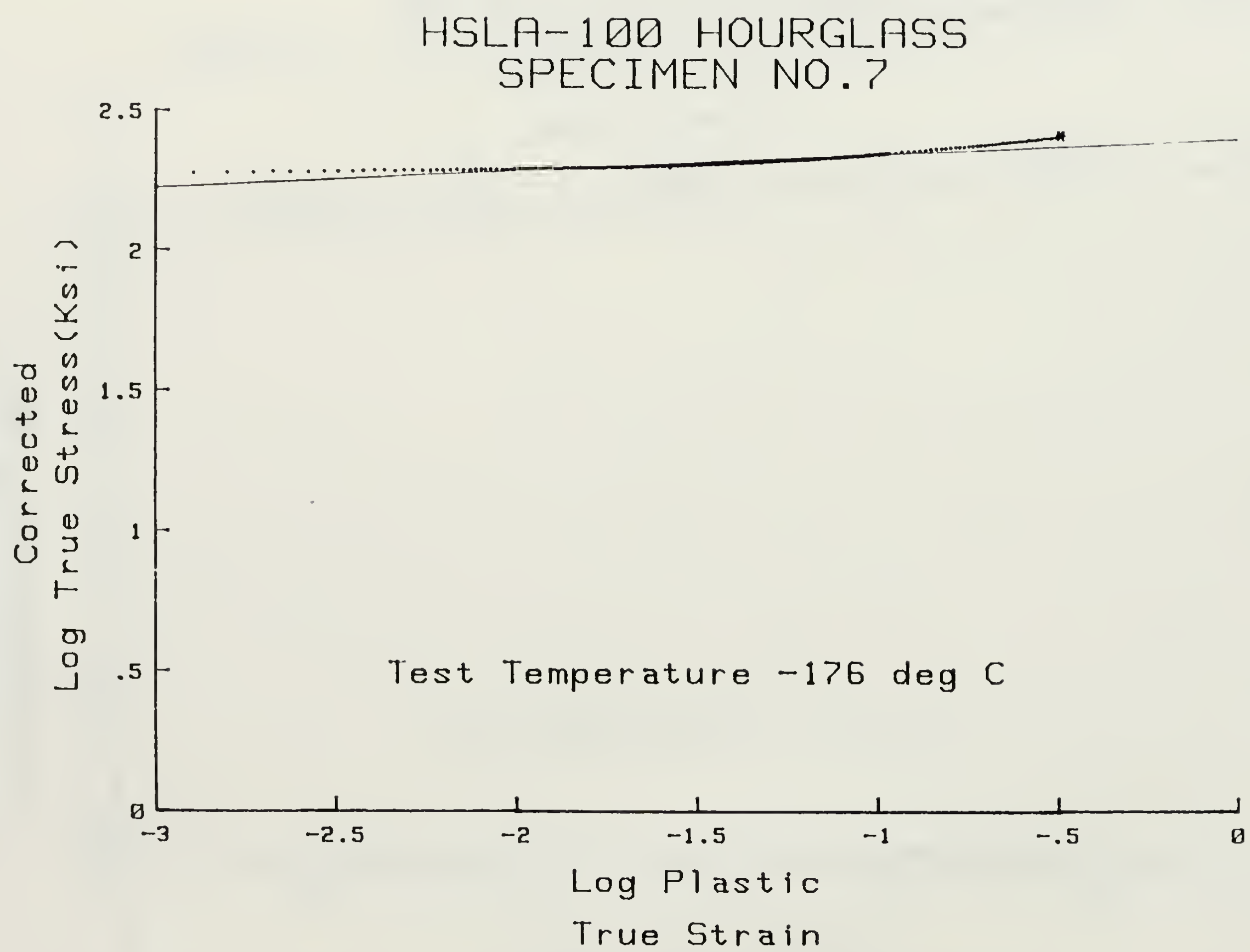


Figure 27. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point

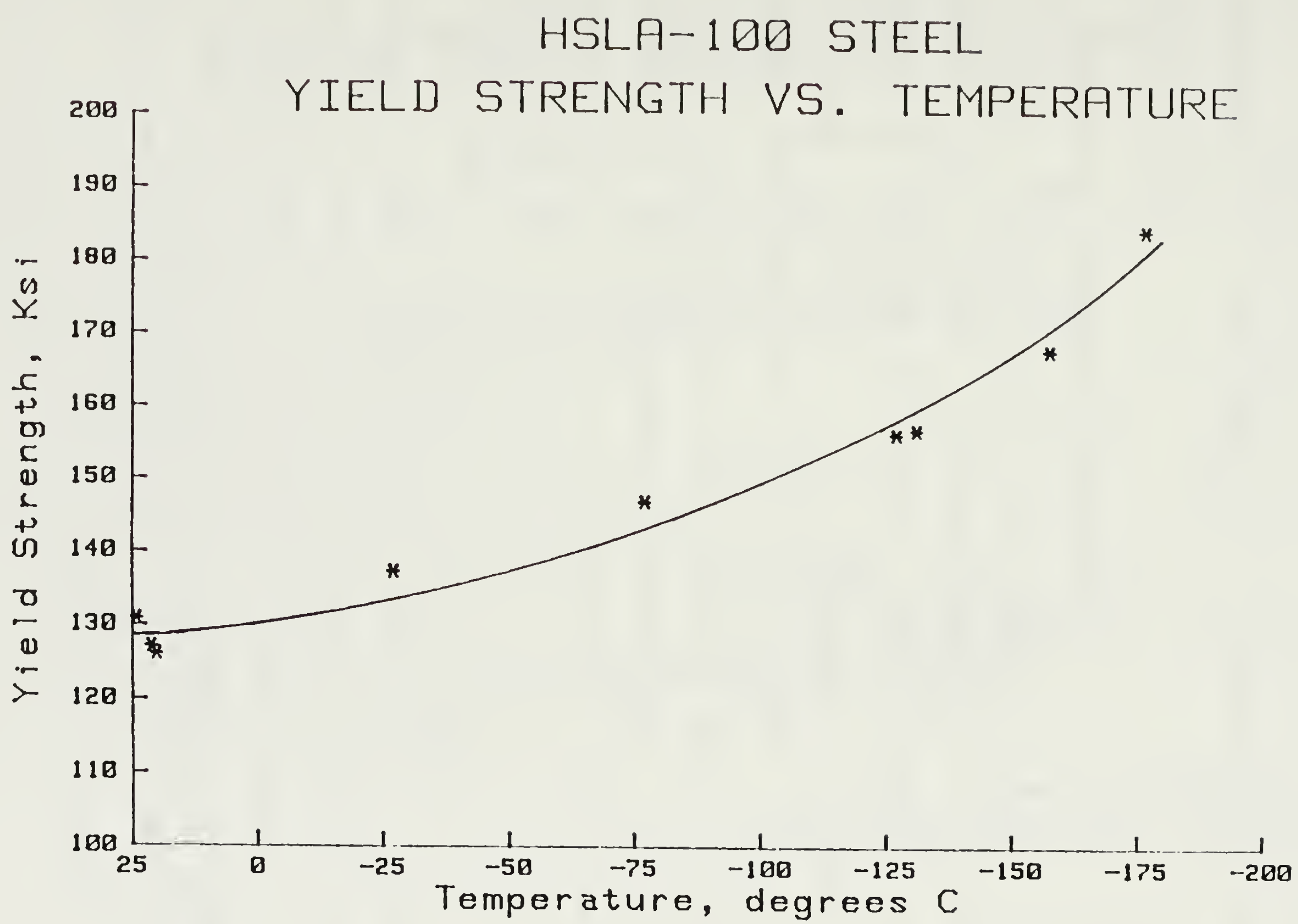


Figure 28. Yield Strength vs. Temperature for the Hourglass Specimens

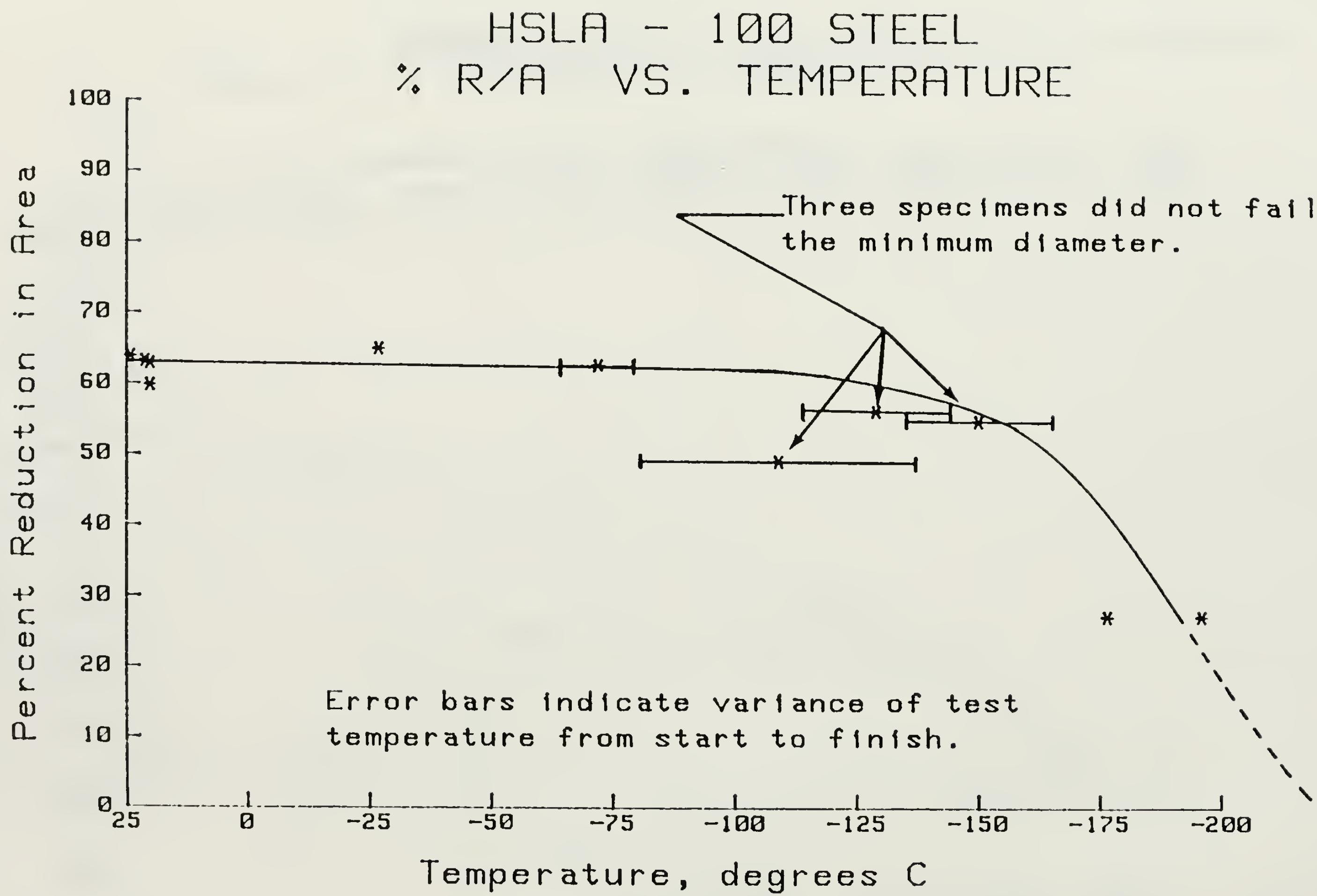


Figure 29. % R/A vs. Temperature for the Hourglass Specimens

diametral extensometer remained in the necked region, following the deformation process throughout these three tensile tests. The fracture surfaces of specimens 6, 11 and 12, revealed a mixture of ductile and cleavage behavior. All three experienced axial cracking (parallel to the specimen axis). A disussion on the cracks, known as delaminations or separations, is contained in the section titled microscopy oberservations.

E. CONSTITUTIVE EQUATION TESTING

In this research the Holloman power function, described earlier, was tested for applicability as a constitutive equation to describe the stress - strain behavior of HSLA - 100 steel. Table III is a tabulation of power law fit constants determined for each test specimen. The constants were determined using a least squares approximation (as discussed in the experimental section [Ref. 30]) to the log true corrected stress - log true plastic strain behavior of the material.

A value of R equal to one is a perfect fit of the straight line; a correlation above .98 is considered a good fit. The calculations necessary to produce the results listed in Table III are preformed by the program in Appendix F. The wide variation in the strength coefficient, and strain hardening exponent and the low values of the

correlation coefficient indicate that the Holloman power law is not very applicable to HSLA - 100 Steel.

TABLE III

CONSTANTS FOR POWER LAW FIT (HOURGLASS SPECIMEN)

No.	Temperature (deg C)	Strain Rate $\times 10^{-4}$/sec	Strain Hardening Exponent n	Strength Coefficient K (ksi)	Correlation Coefficient R
4	20	9.30	0.0464	183.0	.981
5	24	9.26	0.0779	204.2	.972
6	-109	9.30	0.0721	225.7	.962
7	-176	9.26	0.0585	255.9	.911
8	-196	9.35	a	a	a
9	-72	9.26	0.0660	213.3	.980
10	-27	9.26	0.0610	204.9	.989
11	-150	9.35	0.0600	237.0	.971
12	-129	9.30	0.0783	240.3	.975
	UNIFORM GAGE-LENGTH SPECIMEN				
1	20	4.34	0.0465	173.6	.989
2	22	9.28	0.0402	164.7	.969

a - no data collected.

The apparent good fit illustrated in Figures 26 and 27 is lost when the corrected log true stress scale is expanded. An expanded corrected log true stress versus log plastic true strain plot is shown for specimens 9 and 10, whose correlation coefficients were high (above .980), in Figures 30 and 31. The data follows a flattened " S " shape instead of the straight line as predicted by the Holloman power law. This flattened " S " shape was observed in the corrected log true stress - log plastic true strain plots

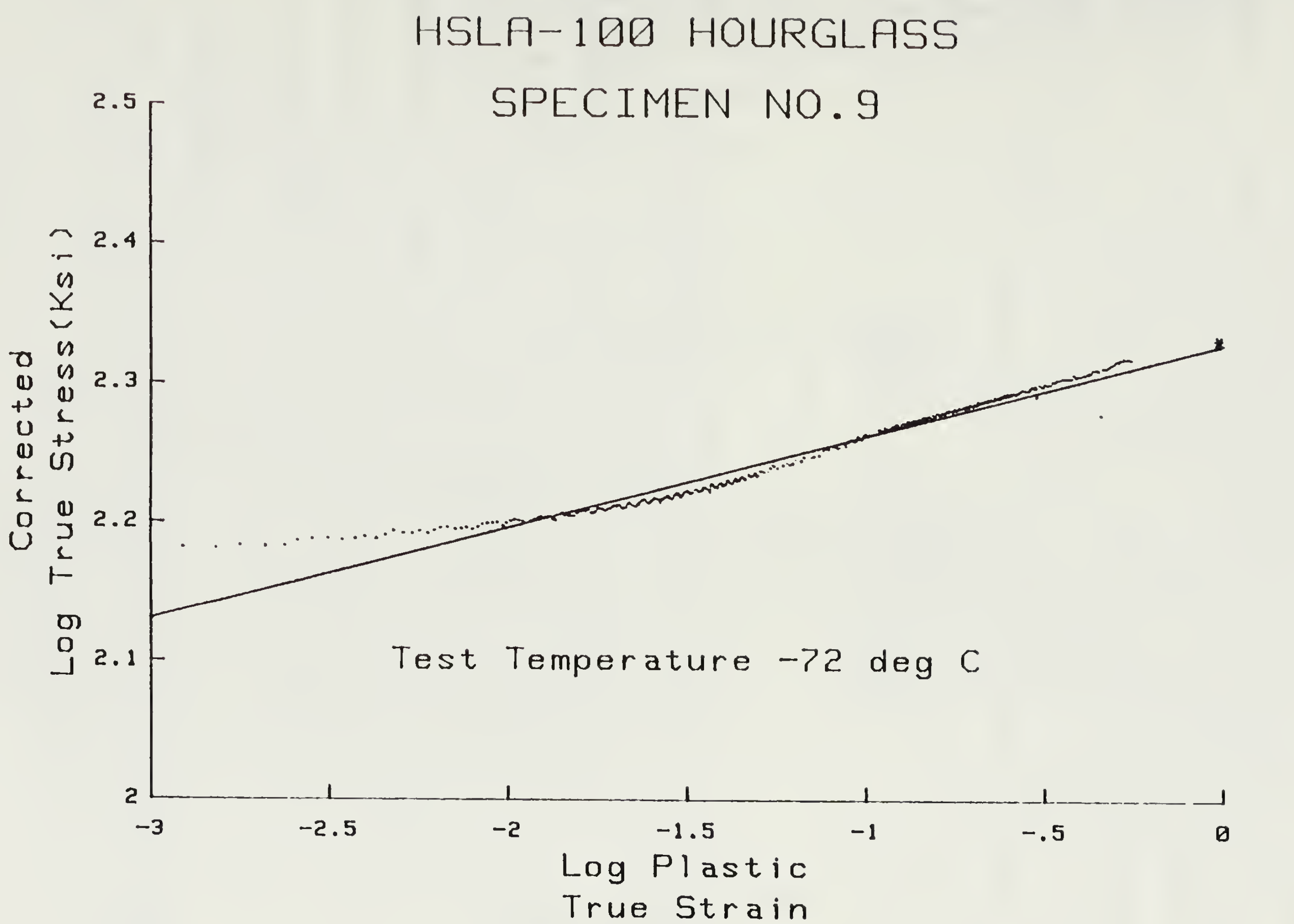


Figure 30. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 9, Tested at -72 C, * Indicates Fracture Point

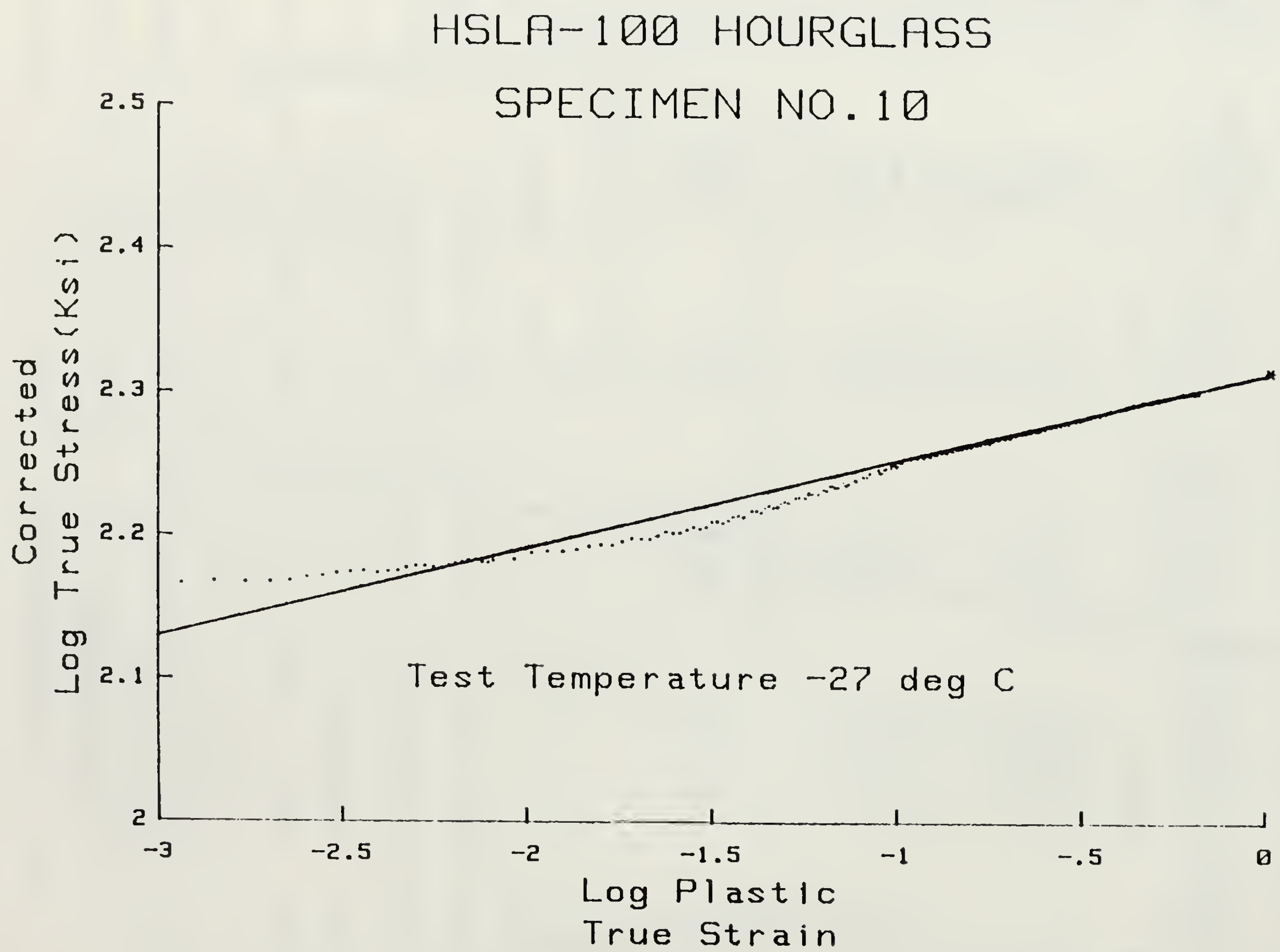


Figure 31. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 10, Tested at -27 C, * Indicates Fracture Point

for all the specimens tested. Closer scrunity of Figures 26 and 27, for specimens 5 and 7, reveals a flattened " S " shaped curve even on the broad corrected log true stress scale.

Conway [Ref. 21:pp. 163-169] discusses an alternative stress - strain relation when the use of the power law is precluded. When the log true stress - log true strain curve results in a flattened " S " shape, see Figures 24 and 25, the power law is not applicable. The alternative stress - strain relation, purported to accurately describe the type of behavior reported herein, is the Voce relation [Ref. 18]. The Voce relation is expressed as follows:

$$S = S_{\infty} - (S_{\infty} - S_0)\, e^{-\epsilon/k}$$

Where S is the true stress, S the final constant stress attained at very large strains, S is the initial stress corresponding roughly with the 0.1% yield stress. is the true strain, k is a constant and e represents the natural logarithm function. A development of the Voce relation is presented by Conway [Ref. 21:pp. 160-174]. Although the Voce relation will not discussed further herein, a logical follow on to this work would be to test its applicability.

F. FRACTOGRAPHY

With the exception of the samples tested below -150 C, the fracture surfaces were characterized by delaminations,

which occurred as cracks running parallel to the rolling direction. The specimens tested between -100 C and -150 C did not fail at the minimum diameter. In these specimens the actual fracture surface occurred between .125 in. and .150 in. from the minimum diameter. Two of these failures occurred above the minimum diameter and one occurred below the minimum diameter.

Figure 32 is a photograph of the specimen tested at -109 C and is typical of the specimens which did not fail at the minimum diameter. In Figure 32 the delamination, running parallel to the specimen longitudinal axis is quite evident. The fracture surface of this specimen is characterized by a mixed ductile-brittle fracture mode, Figure 33. Near the delamination very fine microvoids, characteristic of ductile failure, are evident. While further from the delamination clevage facets prevailed. These failure modes, ductile and brittle can be seen more clearly in Figures 34 (a) and 34 (b), respectively. The orgin of the delaminations, which are planes of weakness parallel to the deformation direction, is still controversial. One possible explanation is that an aligned microstructure, due to the deformation, coupled with inclusions and/or grain boundary carbides provide the weak interfaces which allow the delamination to occur [Ref. 31]. However, other authors have reported that this is not the sole mechanism contributing to this behavior; but that crystallographic texture is also important [Refs. 32, 33].

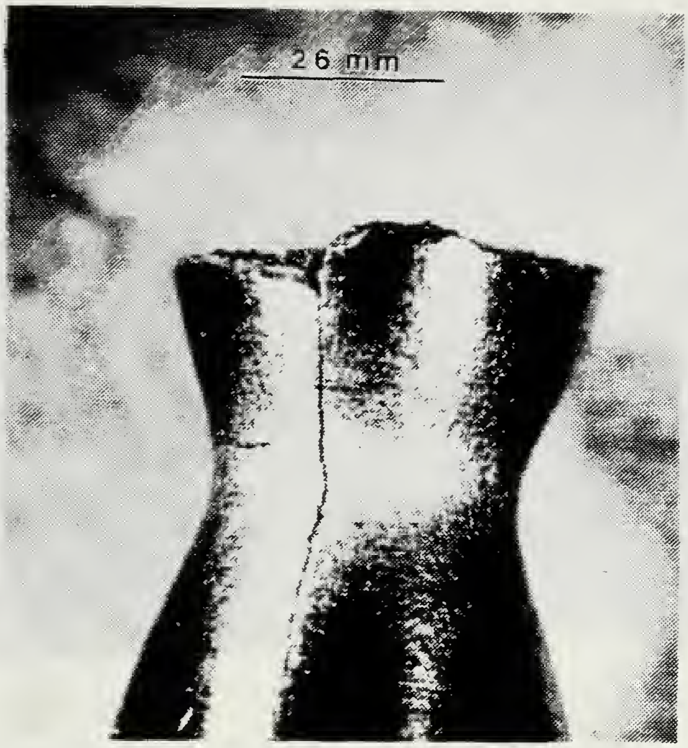


Figure 32. Hourglass Specimen No. 6

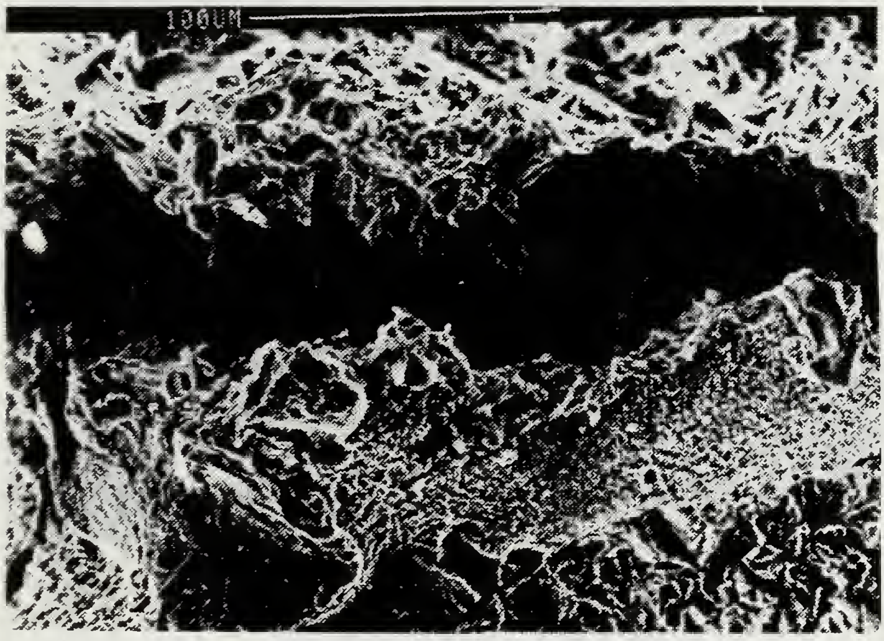
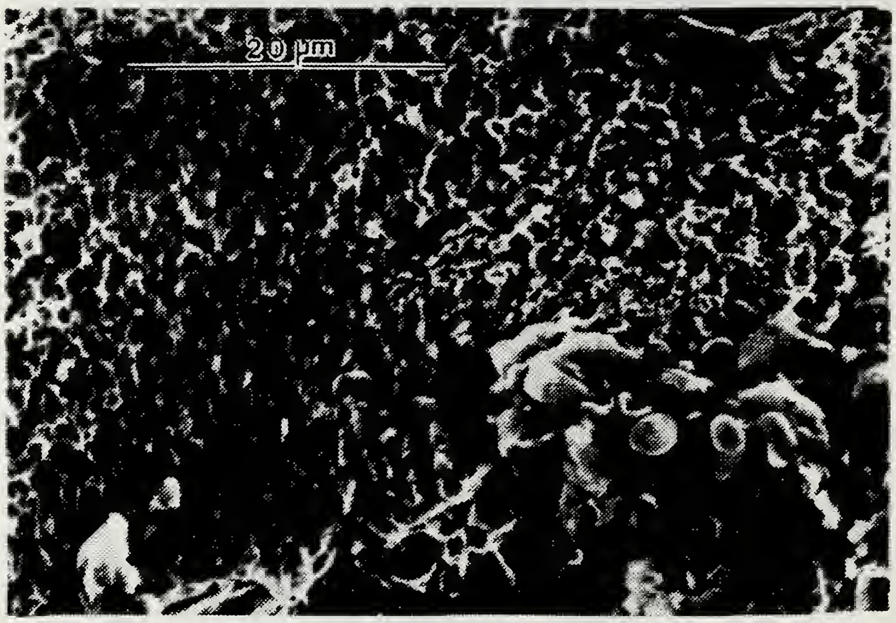
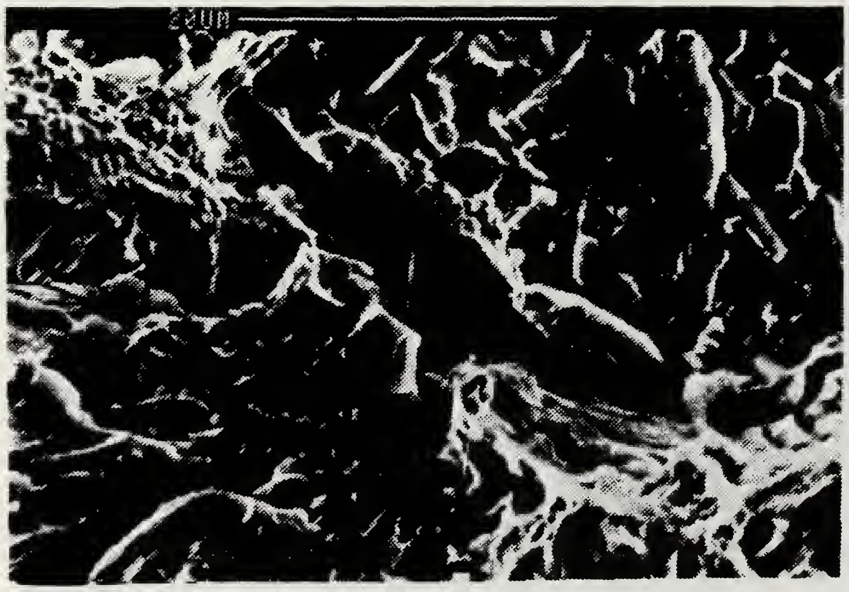


Figure 33. Fracture Surface of Hourglass Specimen No. 6



(a)



(b)

Figure 34. Fracture Surface of Specimen No. 6 (a) Adjacent to the Delamination (b) Adjacent to the area in (a), away from the Delamination

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The HSLA - 100 steel tested in this research has excellent ductility above - 150 C. Rapidly increasing yield strength is observed as temperature decreases.

The Hollomon power function should not be used as the constitutive equation for HSLA - 100 steel as it does not satisfactorily describe the stress - strain response of this steel.

B. RECOMMENDATIONS

The effect of temperature on the tensile properties of properly heat treated HSLA - 100 steel plate should be determined.

The Voce relation should be tested for applicability as a constitutive equation to describe the stress - strain response of HSLA - 100 steel.

Tensile testing at higher strain rates should be conducted to determine the effect of strain rate, in addition to the effect of temperature, on the toughness behavior of HSLA - 100 steel.

APPENDIX A

INTERIM SPECIFICATION FOR TRIAL COMMERCIAL PRODUCTION OF HSLA-100 STEEL PLATES

Melting, Refining and Casting

The heat shall be fully killed and produced to fine grain practice. It shall be made with a low sulfur practice, vacuum degassed and argon injected with CaSi or Mg for sulfide shape control. The heat shall be ingot cast with bottom-pour molds to ensure good surface.

Chemical Composition

The chemical composition shall be as shown in Table I.

Table I - Chemical Composition (Heat and Product Analysis)

ELEMENT	TARGET for First Heat	Max. % by Weight Unless a Range is Indicated
Carbon	0.04	0.06
Manganese	0.90	0.75 - 1.05
Phosphorus	ALAP*	0.015
Sulfur	ALAP	0.006
Silicon	0.25	0.40
Nickel	3.50	3.35 - 3.65
Chromium	0.60	0.45 - 0.75
Molybdenum	0.60	0.55 - 0.65
Copper	1.60	1.45 - 1.75
Columbium	0.025	0.02 - 0.06
Aluminum	0.030	0.020 - 0.040
Nitrogen	0.010	0.015

* As low as possible

Hot Rolling

Plates 1/4, 3/4, 1-1/4, and 2 in. thick shall be rolled. Extra care shall be taken to minimize rolled-in scale that could later interfere with achieving an adequate cooling rate during quenching from the solution treating temperature. The plates shall be roller leveled while still warm after rolling.

Heat Treatment

All of the plates shall be solution heat treated for one hour at 1650 F (934 C) and platen quenched with high pressure water jets from above and beneath the plate. The quench water shall not exceed 100 F to ensure an efficient quench.

The plates shall be given an age hardening treatment using temperatures and times determined for each plate by preliminary tensile testing of samples from coupons aged at various conditions. Aging conditions for the plates shall be chosen so as to give the tensile properties listed in Table II.

Mechanical Properties

The heat treated material shall meet the tensile property requirements specified in Table II and the impact property requirements specified in Table III.

Table II - Tensile Properties

Ultimate Tensile Strength, psi	To be recorded for Information Only	
Yield Strength, 0.2% Offset, psi	<0.75 in. 100,000 to 120,000	>0.75 in. 100,000 to 115,000
Min. Elongation in 2 in., %	17	18
Min. Reduction Area, Round Specimen, %	--	45

The tensile properties shall be determined as the average value of duplicate specimens from each plate tested in accordance with ASTM method of testing E8. Full thickness flat specimens shall be tested for the 1/4 - in. thick plate and standard round specimens 0.505 in. in diameter shall be tested for the plates 3/4 in. thick and thicker. All specimens shall be taken transverse to the primary rolling direction.

Table III - Impact Properties

Test	Plate Thickness, in.	Specimen Size	Test Temp., F	CVN Energy, ** ft-lb
Charpy V-Notch Transverse	0.25	5mm x 10mm	0 + 3	28
			-120 + 3	15
	0.75, 1.25, 2,00	10mm x 10mm	0 + 3	55
			-120 + 3	30

** Avg. of three tests, minimum.

The Charpy impact properties shall be determined in accordance with ASTM method E23. Three tests transverse to the final rolling direction of the plate shall be conducted. No single value shall fall below the minimum average specified in Table III by more than 5 ft-lb for standard specimens and 2-1/2 ft-lb for half size specimens.

APPENDIX B

CHECKLIST AND EXAMPLE SETTINGS

The purpose of this appendix is to provide a detailed checklist for conducting tensile tests on a Materials Testing System (MTS) 810 series system. The form of this appendix is that of an operators checklist followed by an operational sequence for conduction the constant strain rate tensile test. It provides a sequence of operations and references to information in the system technical manuals Nominal testing parameters are as follows:

1. Strain rate = 9.30×10^{-4} /sec.

2. Total diametral displacement range = 0.072 in.

3. A tensile test will be set up herein using a dual slope, hold at breakpoint, ramp and invert function generator set up to allow full extensometer travel.

4. The initial diameter of the specimen will be 0.25 in. and the initial specimen gage length will be 1.00 in. as in Figure 8 for a hourglass shaped specimen.

5. Note: Safe operation of MTS equipment is contingent upon knowledge contained in the introductory section of the system operating manual.

CHECK PROCEDURE	RECORD ADJUSTMENT	MANUAL REFERENCE
.... CONSOLE TURN ON		
_1. Turn CONSOLE POWER on		413.05 OP, page 2
.... PRELIMINARY ADJUSTMENT		
_2. If the load cell, Extensometer clip-on gage, or LVDT is changed, ensure that the proper range card is installed in the appropriate transducer conditioner. NOTE: CRY-ogenic diametral extensometer model No. 632.19B-21		440.21 OP, page 6 440.22 OP, page 6
.... PROGRAMMING		
_3. Select desired controlled variable. Control panel interlock must be open (RESET lit).	_X_ LOAD ___ STRAIN ___ STROKE	440.31 OP, page 2
_4. Select desired operating range.	LOAD +% FS RANGE Full Scale = + 20 KIP ___ 100 1 _X_ 50 2 ___ 25 3 ___ 10 4	440.21 OP, page 3
	STRAIN + FS=.040 IN. RANGE ___ 100 1 _X_ 50 2 ___ 25 3 ___ 10 4	440.21 OP, page 3
	STROKE + FS FULL SCALE = + 3 in. ___ 100 1 ___ 50 2 ___ 25 3	440.22 OP, page 3

CHECK PROCEDURE	RECORD ADJUSTMENT	MANUAL REFERENCE
	_X_ 10 4	
_5. Adjust Digital Function Generator	CONTROL MODE	410.31 OP,
	___ REMOTE _X_ LOCAL ___ SINGLE CYCLE	
	OUTPUT	
	_X_ RAMP ___ SINE ___ HAVERSINE ___ HAVERSQUARE _X_ INVERT	
	BREAKPOINT	
	REMOTE	
	_X_ NORMAL ___ REVERSE	
	LOCAL _X_ NORMAL ___ REVERSE	
	90 PERCENT	
	_X_ DUAL SLOPE _X_ HOLD AT BRKPT ___ RAMP THRU ZERO ___ MANUAL BRKPT (OVERRIDE)	
	360 RATE 1	
	1000 RATE 2	
_6. Adjust SPAN 1 for desired Digital Function Generator siginal amplitude.	100 SPAN 1	440.13 OP, pages3-7
_7. Adjust Digital Display	INPUT SELECT	430.41 OP,

CHECK PROCEDURE	RECORD ADJUSTMENT	MANUAL REFERENCE
indicator.		page 2
	_X_ 1 (LOAD) _X_ 2 (STRAIN) _X_ 3 (STROKE) __ 4 (INPUT options 4-6 are availabel).	

. . . . FAILSAFE ADJUSTMENTS . . . .

_8. Adjust Limit Detectors, if applicable. NOTE: This step may be performed after test has started. See 440.41 OP, page 5	XDCR 1 (LOAD) _100_ UPPER _X_ (+) ___ (-) _10_ LOWER ___ (+) _X_ (-) _X_ INTERLOCK ___ INDICATE	440.41 OP, page 4
	XDCR 2 (STRAIN) _100_ UPPER _X_ (+) ___ (-) _100_ LOWER ___ (+) _X_ (-) _X_ INTERLOCK ___ INDICATE	440.41 OP, page 4

CHECK PROCEDURE	RECORD ADJUSTMENT	MANUAL REFERENCE
	XDCR 3 (STROKE) 100 UPPER _X_ (+) ____ (-) _100 LOWER ____ (+) _X_ (-) _X_ INTERLOCK ____ INDICATE	440.41 OP, page 4

...... PRELIMINARY ADJUSTMENTS AND HYDRAULIC TURN ON ......

_9. Monitor DC ERROR on the Controller meter. — 440.13 OP, page 8

_10. Null the meter using the SET POINT control. — 440.13 OP, page 3

_11. Push RESET on the Control Panel if it is lit. — 413.05 OP, page 2

NOTE: If at any time RESET will not extinguish, loook for an abnormal condition as described on the last page of this checklist under IN CASE OF SYSTEM SHUTDOWN.

_12. Set AUTO RESET switch to OUT. — 440.14/.14A OP, page 2

_13. Push HYDRAULIC PRESSURE on the Control Panel (LOW pressure condition). — 413.05 OP, page 6

If at any time an emergency occurs, push EMERGENCY STOP

.... INSTALLING THE SPECIMEN ....

CHECK PROCEDURE	RECORD ADJUSTMENT	MANUAL REFERENCE
_14. Lower Hydraulic Actuator to bottom stop; then turn off hydraulic pressure.	SET POINT CONTROL full CCW	
_15. Install specimen in the upper grip. Tighten collar with spanner wrench. Plug thermocouple(s) into receptacles.		
_16. Push reset on Control Panel and select low pressure. By adjusting the SET POINT control CCW slowly raise the actuator up to the specimen. Thread the locking collar into the lower grip, as the actuator moves upward, using the spanner wrench.		
_17. Check that LOAD is zeroed. Adjust if necessary.		440.21 OP, page 6

.... MOUNTING THE EXTENSOMETER ....

_18. The extensometer is clamped to the specimen with a spring-loaded arm on one side and an adjustable stationary arm on the other. The adjustable arm contact can be changed to the desired gage length by loosening the contact hold-down screws, moving the contact to the desired gage length, and the retightening the hold-down screws. To obtain 0.072 in. of diametral travel preset extensometer to near -9.0 volts then adjust to -9.000 volts using the zero adjust.		See Technical Manual-TRANSDUCERS

.... ZERO ADJUSTMENT ....

_19. Once the extensometer is attached to the specimen, its electrical output may be adjusted to desired voltage using the zero adjust on the strain transducer conditioner.		440.21 OP, page 4

20. Turn console power on
21. Select desired test temperature on the temperature controller. Attatch thermocouple to desired locale for controlling the temperature.
22. With the enviromental chamber door closed turn the temperature controller to cool. Open the liquid output valve on the cooling medium container.
23. Bring specimen to the desired test temperature. Ensure that temperature has equilibrated on the specimen by monitoring thermocouple temperatures for the two thermocouples attatched to the specimen.
24. Press return to zero on the function generator.
25. Press MTS 440.37 process controller clear D/A button.
26. Select strain control.
27. Zero contoller meter using set point potentiometer.
28. Press interlock resets on MTS 445 and then MTS 413.
29. Set rate 1 on the function generator to 10 sec. and rate 2 to 1 sec.
30. Turn on the Tektronics oscilloscope.
31. Press start on the function generator. When, in 10 sec., the oscilloscope sweep reaches -9 volts press function generator hold button.
32. Set finction generator rate to 360 sec. and rate 2 to 1000 sec.
33. Zero the controller meter using the set point potentiometer.
34. Clear interlock resets on MTS 445 then MTS 413.
35. Turn on hydraulics in low then switch to high pressure.
36. Turn on the 9826 Hewlitt Packard computer, DVM, printer and plotter.
37. Boot up data collection program "JHCOLLECT". Press run and input the requested values.
38. Set the MTS 445 controller recorder dials to Y1 = load, Y2 = strain and X = stroke, this sends these values to channels 1-3 on the DVM.
39. Set the MTS 445 controller osiclloscope dials to Y1 = load, Y2 = off, and X = strain. Then run leads to the chart recorder. The abscissa is strain and the ordinate is load. Set chart recorder at 1 volt/in.
40. To start the test, press the computer soft key labeled start and release the function generator hold button.
41. If full extensometer travel is reached prior to the specimen fracturing, stop hydraulics and pause the data collection program.
42. Set function generator rate 2 to one sec. and press return to zero.
43. Select stroke control on the MTS 445 controller and zero the meter using the set point potentiometer.
44. Change the controller oscilloscope X dial to stroke.

45. Press interlock resets on the MTS 445 and then the MTS 413.
46. Turn on hydraulics in low pressure then swith to high.
47. Press continue on the data collection program.
48. While ovbserving the chart recorder plot SLOWLY load the specimen to the point of fracture. This is done by manually adjusting the set point control in the clock-wise direction.
49. When the specimen fractures press stop hydraulics on the MTS 413 master control panel.
50. Press test stop on the data collection program.
51. Secure the flow of the cooling medium to the enviromental chamber.
52. Turn off console power. When the enviromental chamber is at room temperature the specimen can be removed.

APPENDIX C

BASIC COMPUTER PROGRAM FOR DATA COLLECTION

```
10    !*******************************************
20    ! PROGRAM STORED AS 'JHCOLLECT'             *
30    ! TENSILE CHARACTERISTICS VS TEMP HSLA 100  *
40    ! THE PURPOSE OF THE PROGRAM IS TO COLLECT  *
50    ! THE FOLLOWING FOUR PARAMETERS DURING      *
60    ! CONSTANT STRAIN RATE TENSILE TESTS AT     *
70    ! VARIOUS TEMPFRATURES. THE DATA IS STORED  *
80    ! IN ARRAYS FOR SUBSEQUENT MANIPULATION AND *
90    ! PLOTTING. THE PROGRAM ALSO ALLOWS PLOT-   *
100   ! OF THE LOAD VS. DIAMETRAL DISPLACEMENT    *
110   ! DATA OBTAINED HEREIN.                     *
120   ! PARAMETERS:                               *
130   !     Lod  =  LOAD                          *
140   !     Dia  =  DIAMETRAL DISPLACEMENT        *
150   !     Stk  =  MACHINE ACTUATOR STROKE       *
160   !     Itime =  TIME OF TEST RUN             *
170   !*******************************************
180   !
190   ! DIMENSION THE ARRAYS FOR STORING DATA
200     DIM Lod(500),Stk(500),Dia(500),Itime(500)
210     PRINTER IS 1!CRT
220  Select_: ! CREAT DATA FILES
230     PRINT "Select program using softkeys."
240     OFF KEY
250     ON KEY 0 LABEL "CREATE BDATA" GOTO D_form
260     ON KEY 4 LABEL "RENAME DATA FILE" GOTO R_nam
270     ON KEY 5 LABEL "E   STOP" GOTO S_10
280     ON KEY 9 LABEL "RUN TEST" GOTO T_est
290  Start_idle:    GOTO Start_idle
300  T_est:  !
310     End_test=0 !0 for test in prog 1 for test stopped
320     Dvm=709 ! ADDRESS OF HP3497A
330     CLEAR Dvm  !INITIALIZES HP3497A
340  Set_up:   ! INITIALIZE MTS TEST SET UP
350     PRINTER IS 1
360     PRINT USING "@,#"
370     OFF KEY
380     PRINT "ENTER LOAD TRANSDUCER RANGE 1-4"
390     PRINT "OR PRESS KEY 0 FOR CANNED DATA"
400     Icond=1  ! TRANSDUCER CONDITIONER #1
410     GOSUB Range_set
420     PRINT "ENTER STRAIN TRANSDUCER RANGE 1-4"
430     Icond=2   ! TRANSDUCER CONDITIONER #2
440     GOSUB Range_set
450     PRINT "CHOOSE EXTENSOMETER TYPE",Extenso$,"THEN CONTINUE"
460  Strain_go:     OFF KEY
470     ON KEY 0 LABEL "DIAMETRAL" GOTO Diam
480     ON KEY 4 LABEL "LONGITUDINAL" GOTO Long
490     ON KEY 9 LABEL "CONTINUE" GOTO Axe
500  Strain_wait:  GOTO Strain_wait
510  Axe:!
520     PRINT "EXTENSOMETER TYPE IS ",Extenso$
530     BEEP 300,.5
540     PRINT "ENSURE PROPER DISPLACEMENT IS ENTERED WHEN REQUESTED"
550     PRINT "ENTER STROKE TRANDUCER RANGE 1-4"
560     Icond=3   ! TRANSDUCER CONDITIONER #3
570     GOSUB Range_set
580     OFF KEY
590     Initstr=0 !THIS IS THE STARTING POINT FOR ACTUATOR STROKE
600     Instr=0 !THIS IS THE STARTING POINT FOR THE EXTENSOMETER
```

```
610   BEEP 500..3
620   PRINTER IS 1
630   PRINT USING "@.#"
640   PRINT "TURN ON THE DVM!!!!!!!!!!!!"
650   PRINT
660   PRINT "CHANGE THE DISC????????????"
670   PRINT "ENSURE MTS HYDRAULICS IN HIGH PRESSURE AT THIS POINT"
680   PRINT "PRESS 'CONTINUE' TO RESUME "
690   PAUSE
700   OUTPUT Dvm;"VR5 AF1 AL3"  !SETS CHANNELS 1-3 TO AUTO RANGE
710   OUTPUT Dvm;"AI3 VT1" !READS PRESENT STROKE
720   ENTER Dvm;St
730   OUTPUT Dvm;"AI2 VT1" !READS PRESENT STRAIN
740   ENTER Dvm;Str
750   PRINT " INITIAL STROKE PER DVM=";St
760   PRINT " INITIAL STRAIN PER DVM=";Str
770   Bstroke=Initstr-Istroke*St!BSTROKE SET BY INITIAL CONDITIONS
780   INPUT "Specify maximum strain transducer output, V",Max_str
790   INPUT "Specify displacement at this voltage,in inches",Max_disp
800   ! THE FOLLOWING ACCOUNTS FOR TRANSDUCER RANGE SETTINGS
810   Istrain=Istrain*(Max_disp/Max_str)
820   Bstrain=Instr-Istrain*Str!BSTRAIN SET BY INITIAL CONDITIONS
830   GOTO G_1
840 Long:  !
850         Extenso$="Longitudinal"
860         GOTO Strain_go
870 Diam:!
880         Extenso$="Diametral"
890         GOTO Strain_go
900 G_1:INPUT "Gauge length, inches?",Gage
910      PRINT "gage length=";Gage;" inches"
920   INPUT "Initial diameter, inches?",D_0
930   A_0=(PI/4)*(D_0^2)
940   GOTO Begin
950 Range_set: ! SUBROUTINE TO INPUT RANGES AND TO CONVERT
960  ! VOLTAGES TO ENGINEERING UNITS
970   OFF KEY
980   ON KEY 0 LABEL "TEST DATA" GOTO Test_dat
990   ON KEY 1 LABEL "RANGE 1 = 100%" GOTO R_1
1000  ON KEY 2 LABEL "RANGE 2 = 50% " GOTO R_2
1010  ON KEY 3 LABEL "RANGE 3 = 20% " GOTO R_3
1020  ON KEY 4 LABEL "RANGE 4 = 10% " GOTO R_4
1030 R_s: GOTO R_s
1040 R_1:  PRINT "Range 1 selected."
1050  IF Icond=1 THEN Iload=2.0
1060  IF Icond=2 THEN Istrain=1.0
1070  IF Icond=3 THEN Istroke=.50
1080  RETURN
1090 R_2:PRINT "Range 2 selected."
1100  IF Icond=1 THEN Iload=1.0
1110  IF Icond=2 THEN Istrain=.5
1120  IF Icond=3 THEN Istroke=.250
1130  RETURN
1140 R_3:PRINT "Range 3 selected."
1150  IF Icond=1 THEN Iload=.4
1160  IF Icond=2 THEN Istrain=.2
1170  IF Icond=3 THEN Istroke=.100
1180  RETURN
1190 R_4:PRINT "Range 4 selected."
1200  IF Icond=1 THEN Iload=.2
```

```
1210  IF Icond=2 THEN Istrain=.10
1220  IF Icond=3 THEN Istroke=.050
1230  RETURN
1240 Begin:!still setting up
1250  I=1
1260  INPUT "HOW MANY READINGS PER TEST 500 MAX?",Rdg
1270  PRINT Rdg:" readings selected."
1280  PRINT "THE INTERNAL TRIGGERING OF THE DVM"
1290  PRINT "ALLOWS APPROXIMATELY 2 READINGS OF THE"
1300  PRINT "FOUR VARIABLES PER SECOND WITH NO ADDITIONAL DELAY"
1310  INPUT "ADDITIONAL SECONDS BETWEEN READINGS 1 AND 50",Delay
1320  INPUT "ADDITIONAL SECONDS BETWEEN READINGS 51 AND 200",Delay1
1330  INPUT "ADDITIONAL SECONDS BETWEEN READINGS 201 AND 400",Delay2
1340  INPUT "ADDITIONAL SECONDS BETWEEN READINGS 401 AND 500",Delay3
1350 Cal_x: !
1360  OFF KEY
1370  PRINT
1380  PRINT "TEST SET UP AS FOLLOWS:"
1390  PRINT "FOR ICOND=1, 1 VOLT = ";Iload;"Kip"
1400  PRINT "FOR ICOND=2, 1 VOLT = ";Istrain;"IN"
1410  PRINT "FOR ICOND=3, 1 VOLT = ";Istroke;"IN"
1420  PRINT
1430  PRINT "TYPE EXTENSOMETER IS ";Extenso$
1440  PRINT "NUMBER OF READINGS =";Rdg
1450  PRINT "DELAY BETWEEN READINGS 0-50=";Delay;"SECONDS"
1460  PRINT "DELAY BETWEEN READINGS 51-200=";Delay1;"SECONDS"
1470  PRINT "DELAY BETWEEN READINGS 201-400=";Delay2;"SECONDS"
1480  PRINT "DELAY BETWEEN READINGS 401-500=";Delay3;"SECONDS"
1490  PRINT "Press softkey to start or to change set up."
1500  BEEP 1000,.1
1510  ON KEY 0 LABEL "Start" GOTO Starter
1520  ON KEY 2 LABEL "Fix G.L." GOTO G_l
1530  ON KEY 4 LABEL "Change" GOTO Set_up
1540 Begin_idle:  GOTO Begin_idle
1550 Starter:!
1560  PRINT "Data Acquiring"
1570  OFF KEY
1580 Starter2:!This interrupts data acq & restarts when "CONTINUE" is press
1590  ON KEY 1 LABEL "pause" GOTO Test_pause
1600  ON KEY 4 LABEL "STOP" GOTO Test_complete
1610    IF I<=50 THEN WAIT Delay
1620    IF I>50 AND I<200 THEN WAIT Delay1
1630    IF I>200 AND I<400 THEN WAIT Delay2
1640    IF I>400 THEN WAIT Delay3
1650 Data_acq: ! DATA ACQUISITION ROUTINE
1660  IF I=1 THEN T_0=TIMEDATE
1670  OUTPUT Dvm;"VR5 AF0 AL3"  !SETS CHANNELS 1-3 TO AUTO RANGE
1680  OUTPUT Dvm;"AI1 VT1"      !READS LOAD
1690  ENTER Dvm;Lod(I)          !PUTS VOLTS INTO VARIABLE
1700  OUTPUT Dvm;"AI2 VT1"      !READS STRAIN
1710  ENTER Dvm;Dia(I)          !PUTS VOLTS INTO VARIABLE
1720  OUTPUT Dvm;"AI3 VT1"      !READS STROKE
1730  ENTER Dvm;Stk(I)          !PUTS VOLTS INTO VARIABLE
1740  Itime(I)=TIMEDATE-T_0
1750  I=I+1
1760  Lrdg=I ! LAST READING COUNTER FOR STOPPING TEST
1770  IF I>Rdg OR I>499 THEN Stopper
1780  GOTO Starter2
1790 Stopper: !
1800  PRINT "ACQUISITION COMPLETE"
```

```
1810  Count_out=1 ! COUNTING AND SORTING VARIABLE
1820 Conv_ss: !
1830  !CONVERT VOLTAGE DATA TO ENG UNITS LOAD,TEMP,STROKE,DISPL
1840  Lrdg=Lrdg-1
1850  FOR H=1 TO Lrdg
1860    Lod(H)=Lod(H)*Iload
1870    Stk(H)=Stk(H)*Istroke+Bstroke
1880    Dia(H)=Dia(H)*Istrain+Bstrain
1890    NEXT H
1900  !STORE DATA AS CONVERTED TO BDAT FILES
1910  OFF KEY
1920 Dat_out:!
1930  PRINTER IS 1
1940  PRINT USING "@,#"
1950  PRINT "Data is being stored. Sorry for the delay......"
1960  PRINT "Assigning to Load, etc."
1970  ASSIGN @Path1 TO "Lod"
1980  ASSIGN @Path2 TO "Dia"
1990  ASSIGN @Path3 TO "Stk"
2000  ASSIGN @Path4 TO "Itime"
2010  FOR I=1 TO Lrdg
2020    OUTPUT @Path1;Lod(I)
2030    OUTPUT @Path2;Dia(I)
2040    OUTPUT @Path3;Stk(I)
2050    OUTPUT @Path4;Itime(I)
2060    NEXT I
2070  FOR I=1 TO Lrdg
2080  ASSIGN @Path1 TO *
2090  ASSIGN @Path2 TO *
2100  ASSIGN @Path3 TO *
2110  ASSIGN @Path4 TO *
2120  NEXT I
2130  !OUTPUT THE DATA
2140  PRINT USING "@,#"
2150  PRINT "SELECT HARD OR SOFT COPY"
2160  PRINT "LOAD/DISP"
2170  OFF KEY
2180  ON KEY 0 LABEL "HARD COPY" GOTO Har
2190  ON KEY 4 LABEL "NO HARD COPY" GOTO Sof
2200 Stop_idle:  GOTO Stop_idle
2210 Har: PRINTER IS 706
2220 Sof:!
2230  OFF KEY
2240  PRINT "  I          LOAD       DISPL      STROKE      TIME"
2250  PRINT "               (KIP)      (IN)       (IN)       (SEC)"
2260  FOR I=1 TO Lrdg
2270    PRINT USING Fmt1;I,Lod(I),Dia(I),Stk(I),Itime(I)
2280    NEXT I
2290 Fmt1:IMAGE DDD,5X,4(1X,SD.DDE)
2300 OFF KEY
2310 Plotz:  !
2320   DEG
2330   OFF KEY
2340   PRINT "Choose whether or not to plot"
2350   ON KEY 4 LABEL "NO PLOT" GOTO N_p
2360   ON KEY 0 LABEL "YES PLOT" GOTO Y_p
2370   GOTO 2370
2380 Y_p:  ! PLOT ROUTINE
2390   OFF KEY
2400   GCLEAR
```

```
2410   GINIT
2420   GRAPHICS ON
2430   PLOTTER IS 705,"HPGL"
2440   VIEWPORT 13.5,133.0,10.5,95.0
2450   PEN 1
2460   VIEWPORT 25,110,30,85
2470   IF Count_out=1 THEN
2480     Max_x=.05
2490     Max_y=8
2500     Y_step=8
2510   END IF
2520   WINDOW 0,Max_x,0,Max_y
2530   AXES Max_x/10,Max_y/10,0,0
2540   CSIZE 2.0
2550   VIEWPORT 13.5,133,10.5,95
2560   LORG 4
2570   FOR I=0 TO Max_x STEP Max_x/10
2580      MOVE I,-Max_y/20
2590      LABEL USING "K";I
2600      NEXT I
2610   CSIZE 3
2620   MOVE Max_x/2,-Max_y/10
2630   IF Count_out=1 THEN LABEL USING "K";"Displacement, in"
2640   LORG 8
2650   CSIZE 2
2660   FOR I=0 TO Max_y STEP Max_y/Y_step
2670      MOVE -Max_x/35,I
2680      LABEL USING "K";I
2690      NEXT I
2700   CSIZE 3
2710   LDIR 90
2720   LORG 6
2730   MOVE -Max_x/8,Max_y/2
2740   IF Count_out=1 THEN LABEL USING "K";"Load, Kip"
2750   LDIR 0
2760   LORG 5
2770   CSIZE 1.5
2780   MOVE 0,0
2790   FOR J=1 TO Lrdg
2800     DRAW Dia(J),Lod(J)
2810     NEXT J
2820 N_p:  !
2830   Count_out=Count_out+1
2840   IF Count_out<2 THEN Conv_ss
2850   I=1
2860   PRINT "Run another test? Press soft key"
2870   FOR Q=0 TO 3
2880    ON KEY Q LABEL "Run again" GOTO Cal_x
2890    ON KEY Q+5 LABEL "New set up" GOTO Set_up
2900    NEXT Q
2910  ON KEY 4 LABEL "Stop" GOTO S_10
2920  ON KEY 9 LABEL "Stop" GOTO S_10
2930 S_9: GOTO S_9
2940 S_10:STOP
2950 Test_halt:!
2960   Diam=Dia(I)*Istrain+Bstrain
2970   Strk=Stk(I)*Istroke+Bstroke
2980   Lode=Lod(I)*Iload+Bload
2990   PRINT "Test halted at:"
3000   PRINT "dia of ";Diam;" in"
```

```
3010   PRINT "stroke of ";Strk;" in"
3020   PRINT "load of ";Lode;" lbs"
3030   BEEP
3040   GOTO Cal_x
3050 Test_pause: !
3060   OFF KEY
3070   PRINT "TEST PAUSE HIT CONTINUE TO RESUME"
3080   PAUSE
3090   GOTO Data_acq
3100 Test_complete: ! STOPS DATA COLLECTION AND STORES THAT COLLECTED
3110   OFF KEY
3120   GOTO Stopper
3130 Test_dat:!SAMPLE DATA FOR VERIFYING PROGRAM
3140   Istroke=1
3150 ! Istrain=.004 ! FOR DIAM. EXTENSO. RANGE1
3160   Istrain=.010 ! FOR LONG. EXTENSO. RANGE1
3170   Iload=1
3180 ! Bstrain=.040 ! FOR DIAM. EXTENSO. RANGE1
3190   Bstrain=0    ! FOR LONG. EXTENSO.
3200   D_0=.25
3210   A_0=.049
3220   T_0=TIMEDATE
3230   Lrdg=10
3240   FOR I=1 TO 11
3250     Lod(I)=I/2
3260     Stk(I)=I/5
3270 !   Dia(I)=2*I-12 !FOR DIAM. EXTENSO.0-10V
3280     Dia(I)=I      !FOR LONG. EXTENO. 0-10V
3290     Itime(I)=TIMEDATE-T_0
3300     NEXT I
3310   GOTO Stopper
3320 R_nam: !
3330   BEEP 500,.2
3340   BEEP 1000,.2
3350   PRINT "Put in data disc!!!!!!!!!!!!"
3360   PRINT "Hit continue key when ready"
3370   PAUSE
3380   OFF KEY
3390   PRINT "Select old file name using soft keys"
3400   ON KEY 0 LABEL "Lod" GOTO R_nam_1
3410   ON KEY 1 LABEL "Dia" GOTO R_nam_2
3420   ON KEY 2 LABEL "Stk" GOTO R_nam_3
3430   ON KEY 4 LABEL "Itime" GOTO R_nam_5
3440 R_nam_0:  GOTO R_nam_0
3450 R_nam_1:Old_file$="Lod"
3460   GOTO R_nam_8
3470 R_nam_2:Old_file$="Dia"
3480   GOTO R_nam_8
3490 R_nam_3:Old_file$="Stk"
3500   GOTO R_nam_8
3510 R_nam_5:Old_file$="Itime"
3520   GOTO R_nam_8
3530 R_nam_8:  !
3540   OFF KEY
3550   INPUT "What is new file name?",New_file$
3560   RENAME Old_file$ TO New_file$
3570   PRINT USING "@,#"
3580   PRINT "Any more files to rename?"
3590   ON KEY 0 LABEL "MORE FILES" GOTO R_nam
3600   ON KEY 4 LABEL "quit" GOTO Select_
```

```
3610 R_nam_idle:  GOTO R_nam_idle
3620 D_form:!
3630   OFF KEY
3640   ON ERROR GOTO Error_check
3650   PRINTER IS 1
3660   PRINT USING "@,#"
3670   PRINT "Put in data disc!!!!!!!!!!!!"
3680   PRINT "Then hit continue key."
3690   BEEP 100,.2
3700   BEEP 350,.2
3710   BEEP 1000,.2
3720   PAUSE
3730   PRINT "Creating Lod file"
3740   CREATE BDAT "Lod".501,8
3750   PRINT "Creating Dia file"
3760   CREATE BDAT "Dia".501,8
3770   PRINT "Creating Stk file"
3780   CREATE BDAT "Stk",501,8
3790   PRINT "Creating Itime file"
3800   CREATE BDAT "Itime",501,8
3810   GOTO Select_
3820 Error_check:  !
3830   IF ERRN=54 THEN GOTO Select_
3840   PRINT "Error...ERRN is";ERRN
3850   GOTO D_form
3860    END
```

APPENDIX D

BASIC COMPUTER PROGRAM FOR DATA REDUCTION

```
10 !**********************************************
20 !  PROGRAM STORED AS"JHREDUCE"                 *
30 !  PROGRAM TO CALCULATE STRESS/STRAIN ....     *
40 !  FROM THE DATA COLLECTED IN "JHCOLLECT"      *
50 !  THEN STORE CALCULATED VALUES IN ARRAYS FOR  *
60 !  SUBSEQUENT PLOTTING AND CURVE FITTING       *
70 !  KEY VARIABLES USED:                         *
80 !    Lod = Load                                *
90 !    Dia = Diametral displacement              *
100!    Stress = True Stress                      *
110!    Strain = True Strain                      *
120!    Lstress = Log of True Stress              *
130!    Lstrain = Log of True Strain              *
140!    Cstress = Bridgeman corrected True Stress*
150!    Clstress = Log Bridgeman Cstress          *
160!    Strainp = Plastic True Strain             *
170!    Lstrainp = Log Plastic True Strain        *
180!**********************************************
190!
200!  DIMENSION ARRAYS
210   DIM Lod(500),Stk(500),Dia(500),Itime(500)
220   DIM Stress(500),Strain(500)
230   DIM Lstress(500),Lstrain(500),Cstress(500)
240   DIM Lstrainp(500),Strainp(500),Clstress(500)
250   PRINT " ENSURE THE PROPER FILE NUMBERS"
260   PRINT " ARE LISTED IN THE @PATH STATEMENTS"
270   PRINT " PRIOR TO RUNNING THIS PROGRAM"
280   ! INPUT INITIAL/FINAL SPECIMEN DIAMETERS
290   ! INPUT INITIAL/FINAL NECK RADIUS OF CURVATURES
300   INPUT " ENTER INITIAL SPECIMEN DIAMETER",D_0
310   ! CALCULATE INITIAL CROSS-SECTIONAL AREA A_0
320   A_0=(PI/4)*(D_0^2)
330   PRINT "INITIAL AREA =",A_0
340   INPUT " ENTER FINAL SPECIMEN RADIUS",Rn
350   INPUT " ENTER FINAL NECK RADIUS OF CURVATURE",R
360   !COMPUTE INITIAL(CORRI) AND FINAL (CORRF)
370   !BRIDGEMAN CORRECTION FACTORS
380   ! INITAL CORRECTION CORRI= .9723
390   !THIS FACTOR IS APPLICABLE UP TO NECKING
400   Corri=.9723
410   A=1+(2*R/Rn)
420   B=1+(Rn/(2*R))
430   Corrf=1/(A*LOG(B))
440   PRINT "FINAL CORRECTION FACTOR =",Corrf
450   INPUT "ENTER VALUE FOR YOUNG'S MODULUS",Ym
460   INPUT "ENTER MAX LOAD",Mlod
470   Count_out=1 ! COUNTING VARIABLE
480   IF Count_out>1 THEN GOTO 680
490   INPUT "CREATE FILES ? 1=YES 0= NO",Cre_ate
500   IF Cre_ate>0 THEN
510     PRINT "CREATING STRESS FILE"
520     CREATE BDAT "Stress",501,8
530     PRINT "CREATING STRAIN FILE"
540     CREATE BDAT "Strain",501,8
550     PRINT "CREATING LSTRESS FILE"
560     CREATE BDAT "Lstress",501,8
570     PRINT "CREATING LSTRAIN FILE"
580     CREATE BDAT "Lstrain",501,8
590     PRINT "CREATING CSTRESS FILE"
600     CREATE BDAT "Cstress",501,8
```

```
610     PRINT "CREATING CLSTRESS FILE"
620     CREATE BDAT "Clstress",501,8
630     PRINT "CREATING STRAINP FILE"
640     CREATE BDAT "Strainp",501,8
650     PRINT "CREATING LSTRAINP FILE"
660     CREATE BDAT "Lstrainp",501,8
670   END IF
680 ! INPUT THE PROPER Lod AND Dia FILE NUMBER
690 ! THE FILES NUMBERS MATCH THE SPECIMEN NO.
700 ! i.e. ASSIGN @PATH1 TO "Lod1"
710 BEEP 300,.5
720 PRINT " ENSURE PROPER LOD/DIA FILE DISC IN"
730 PRINT " PRESS CONTINUE TO PROCEED"
740 PAUSE
750   ASSIGN @Path1 TO "Lod"
760   ASSIGN @Path2 TO "Dia"
770 ! PATHS 3 AND 4 ARE FOR ACTUATOR STROKE AND
780 ! TEST RUN TIME AND ARE NOT USED IN PROGRAM
790 ! ENTER INTO LOD/DIA ARRAYS THE VALUES OF THE
800 ! APPROPRIATE DATA FILE FOR CALCULATION OF
810 ! STRESS,STRAIN....
820   INPUT "Specify number of data points 500 max",Rdg
830   FOR I=1 TO Rdg
840     ENTER @Path1;Lod(I)
850     ENTER @Path2;Dia(I)
860      IF Count_out=1 THEN
870       IF Lod(I)>=Mlod THEN
880         Mlod=Lod(I)  ! MAX-LOAD
890         Juts=I          ! DATA POINT AT MAX-LOAD
900  ! THIS IS POINT WHERE THE LINEAR CORRECTION
910  ! BEGINS TO BE APPLIED, SEE ARRAY_ASSIGN
920         PRINT "READING=",Juts
930         PRINT "MLOD=",Mlod
940         Mdia=Dia(I) ! DISP. AT MAX-LOAD
950         PRINT "MDIA=",Mdia
960         GOTO Correct_b
970       ELSE
980         Juts=Rdg
990       END IF
1000     END IF
1010  NEXT I
1020  GOTO 1230
1030  !
1040 Correct_b:  !DETERMINE SLOPE AND INTERCEPT
1050  ! VALUES TO APPLY LINEAR BRIDGEMAN
1060  ! CORRECTION TO POINTS AFTER NECKING
1070  A_uts=(PI/4)*((D_0-Mdia)^2)!AREA AT MAX-LOAD
1080  Stressuts=Mlod/A_uts ! STRESS=UTS
1090  INPUT "LOAD AT FRACTURE=",Flod
1100  INPUT "FINAL DIA=",D_f
1110  A_f=(PI/4)*(D_f^2)
1120  Fstress=Flod/A_f ! STRESS AT FRACTURE
1130  Mb=(Corrf-Corri)/(Fstress-Stressuts)
1140  PRINT "MB=",Mb  !SLOPE FOR LINEAR BRIDGEMAN
1150  !CORRECTION
1160  Intercept=Corrf-(Mb*Fstress) ! INTERCEPT
1170  ! VALUE FOR LINEAR BRIDGEMAN CORRECTION
1180  PRINT "INTERCEPT =",Intercept
1190  Count_out=Count_out+1
1200  ASSIGN @Path1 TO *
```

```
1210  ASSIGN @Path2 TO *
1220  GOTO 680
1230  PRINTER IS 1
1240  BEEP 200,.5
1250  PRINT "INSTALL DISC TO SAVE DATA ON"
1260  PRINT "PRESS CONTINUE TO RESUME"
1270  PAUSE
1280  ASSIGN @Path5 TO "Stress"
1290  ASSIGN @Path6 TO "Strain"
1300  ASSIGN @Path7 TO "Lstress"
1310  ASSIGN @Path8 TO "Lstrain"
1320  ASSIGN @Path9 TO "Cstress"
1330  ASSIGN @Path10 TO "Clstress"
1340  ASSIGN @Path11 TO "Strainp"
1350  ASSIGN @Path12 TO "Lstrainp"
1360  PRINT "ASSINGING VALUES TO ARRAYS"
1370  PRINTER IS 706
1380  ! COMPUTE AND ASSIGN VALUES TO ARRAYS
1390 Array_assign:!
1400   FOR J=1 TO Rdg
1410         Ai=(PI/4)*((D_0-Dia(J))^2)
1420         Stress(J)=Lod(J)/Ai
1430         OUTPUT @Path5;Stress(J)
1440         Strain(J)=LOG(A_0/Ai)
1450         OUTPUT @Path6;Strain(J)
1460     IF Stress(J)<=0 THEN
1470         Lstress(J)=0.
1480     ELSE
1490         Lstress(J)=LGT(Stress(J))
1500     END IF
1510         OUTPUT @Path7;Lstress(J)
1520     IF Strain(J)<=0 THEN
1530         Lstrain(J)=0
1540     ELSE
1550         Lstrain(J)=LGT(Strain(J))
1560     END IF
1570         OUTPUT @Path8;Lstrain(J)
1580     IF J<Juts THEN
1590         Cstress(J)=Corri*Stress(J)
1600     ELSE
1610         Corrb=(Mb*Stress(J))+Intercept
1620         Cstress(J)=Corrb*Stress(J)
1630 !         PRINT "RDG=",Rdg
1640 !         PRINT "Dia =",Dia(J)
1650 !         PRINT "Corrb=",Corrb
1660     END IF
1670         OUTPUT @Path9;Cstress(J)
1680     IF Cstress(J)<=0 THEN
1690         Clstress(J)=0.
1700     ELSE
1710         Clstress(J)=LGT(Cstress(J))
1720     END IF
1730         OUTPUT @Path10;Clstress(J)
1740         Strainp(J)=Strain(J)-(Cstress(J)/Ym)
1750         OUTPUT @Path11;Strainp(J)
1760     IF Strainp(J)<=0 THEN
1770         Lstrainp(J)=0.
1780     ELSE
1790         Lstrainp(J)=LGT(Strainp(J))
1800     END IF
```

```
1810          OUTPUT @Path12:Lstrainp(J)
1820   !      PRINT "rdg's complete=",J
1830   NEXT J
1840   PRINTER IS 1
1850   BEEP 500,1
1860   PRINT "INSTALL DISC WITH LOAD/DIA DATA "
1870   PRINT "PRESS CONTINUE TO CLOSE PATHS"
1880   PAUSE
1890   ASSIGN @Path1 TO *
1900   ASSIGN @Path2 TO *
1910   BEEP 250,.5
1920   PRINT "INSTALL STRESS/STRAIN...DATA DISC"
1930   PRINT "PRESS CONTINUE"
1940   PAUSE
1950   ASSIGN @Path5 TO *
1960   ASSIGN @Path6 TO *
1970   ASSIGN @Path7 TO *
1980   ASSIGN @Path8 TO *
1990   ASSIGN @Path9 TO *
2000   ASSIGN @Path10 TO *
2010   ASSIGN @Path11 TO *
2020   ASSIGN @Path12 TO *
2030   INPUT "RENAME FILES? 1=YES 0=NO",C_nt
2040   PRINT "FILE SHOULD BE RENAMED USING"
2050   PRINT "THE APPROPRIATE SECIMEN NO."
2060   IF C_nt<1 THEN
2070     GOTO 2510
2080   END IF
2090 R_nam: ! ROUTINE TO RENAME FILES
2100    BEEP 500,.2
2110    BEEP 1000,.2
2120    PRINT "Put in data disc!!!!!!!!!!!!"
2130    PRINT "Hit continue key when ready"
2140    PAUSE
2150    OFF KEY
2160    PRINT "Select old file name using soft keys"
2170    ON KEY 0 LABEL "Stress" GOTO R_nam_1
2180    ON KEY 1 LABEL "Strain" GOTO R_nam_2
2190    ON KEY 2 LABEL "Lstress" GOTO R_nam_3
2200    ON KEY 3 LABEL "Lstrain" GOTO R_nam_4
2210    ON KEY 4 LABEL "Cstress" GOTO R_nam_5
2220    ON KEY 5 LABEL "Clstress" GOTO R_nam_6
2230    ON KEY 6 LABEL "Strainp" GOTO R_nam_7
2240    ON KEY 7 LABEL "Lstrainp" GOTO R_nam_8
2250 R_nam_0:  GOTO R_nam_0
2260 R_nam_1:Old_file$="Stress"
2270    GOTO R_nam_9
2280 R_nam_2:Old_file$="Strain"
2290    GOTO R_nam_9
2300 R_nam_3:Old_file$="Lstress"
2310    GOTO R_nam_9
2320 R_nam_4:Old_file$="Lstrain"
2330    GOTO R_nam_9
2340 R_nam_5:Old_file$="Cstress"
2350    GOTO R_nam_9
2360 R_nam_6:Old_file$="Clstress"
2370    GOTO R_nam_9
2380 R_nam_7:Old_file$="Strainp"
2390    GOTO R_nam_9
2400 R_nam_8:Old_file$="Lstrainp"
```

```
2410 R_nam_9:!
2420   OFF KEY
2430   INPUT "What is new file name?",New_file$
2440   RENAME Old_file$ TO New_file$
2450   PRINT USING "@,#"
2460   PRINT "Any more files to rename?"
2470   ON KEY 0 LABEL "MORE FILES" GOTO R_nam
2480   ON KEY 4 LABEL "quit" GOTO 2510
2490 R_nam_idle:  GOTO R_nam_idle
2500  BEEP 200,.5
2510   PRINT "PROGRAM  COMPLETED "
2520    END
```

APPENDIX E

BASIC COMPUTER PROGRAM FOR DATA DISPLAY

```
10     !*******************************************
20     ! PROGRAM "JHPLOT"                          *
30     ! THE PURPOSE OF THIS PROGRAM IS TO PLOT    *
40     ! THE DATA COLLECTED BY "JHCOLLECT".        *
50     ! THE BELOW LISTED GENERIC ARRAYS MUST      *
60     ! INCLUDE A SPECIMEN NO. i.e. Lod1,Dia1... *
70     ! THE ARRAYS ARE:                           *
80     !   Lod( )= THE LOAD VALUES                 *
90     !   Dia( )= THE DIAMETRAL DISPLACEMENTS     *
100    !   Stk( )= MTS ACTUATOR STROKE VALUES      *
110    !   Itime( )= TEST RUN TIME                 *
120    !   Stress( )= TRUE STRESS VALUES           *
130    !   Strain( )= TRUE STRAIN VALUES           *
140    !   Lstress()= LOG TRUE STRESS VALUES       *
150    !   Lstrain( )= LOG TRUE STRAIN VALUES      *
160    !   Cstress( )= BRIDGEMAN CORRECTED TRUE    *
170    !               STRESS VALUES               *
180    !   Clstress( )= LOG BRIDGEMAN CORRECTED    *
190    !                TRUE STRESS VALUES         *
200    !   Strainp( )= PLASTIC TRUE STRAIN VALUES *
210    !   Lstrainp( )= LOG PLASTIC TRUE STRAIN    *
220    !                VALUES                     *
230    !*******************************************
240    !
250    ! DIMENSION THE ARRAYS
260    DIM Lod(500),Stk(500),Dia(500),Itime(500),Stress(500),Strain(500)
270    DIM Lstress(500),Lstrain(500),Cstress(500)
280    DIM Lstrainp(500),Strainp(500),Clstress(500)
290    BEEP 400,.5
300    PRINT " ENSURE THE PROPER FILES TO BE PLOTTED ARE LISTED  IN THE ASSIGN"
310    PRINT " @PATH STATEMENTS PRIOR TO RUNNING THIS PROGRAM"
320    PRINT
330    Count_out=0 !COUNTER
340    INPUT "Specify number of data points 500 max",Rdg
350    ! THE FOLLOWING CALCULATES FRACTURE POINT VALUES
360       INPUT "INITIAL DIAMETER",D_0
370       A_0=(PI/4)*(D_0^2)
380       INPUT "LOAD AT FRACTURE",Flod
390       INPUT "FINAL DIAMETER ",Fdia
400       Rn=Fdia/2 ! FINAL SPECIMEN RADIUS
410       INPUT "FINAL NECK RADIUS OF CURVATURE",R
420       Corrf=1/((1+(2*R/Rn))*(LOG(1+(Rn/(2*R)))))
430       PRINT "FINAL BRIDGEMAN CORR.=";Corrf
440       INPUT "ENTER YOUNG'S MODULUS",Ym
450          A_f=(PI/4)*(Fdia^2)
460          Fstress=Flod/A_f
470          Lfstress=LGT(Fstress)
480          Fstrain=LOG(A_0/A_f)
490          Lfstrain=LGT(Fstrain)
500          Cfstress=Corrf*Fstress
510          Clfstress=LGT(Cfstress)
520          Fstrainp=Fstrain-(Cfstress/Ym)
530          Lfstrainp=LGT(Fstrainp)
540 Stopper:  !
550    IF Rdg>500 THEN GOTO 340
560    PRINT
570    Count_out=Count_out+1
580    PRINT "ASSIGNING PATHS"
590    IF Count_out=1 THEN
600    BEEP 100,.5
```

```
610   PRINT "INSTALL APPROPRIATE DATA DISC"
620   PRINT "PRESS CONTINUE TO RESUME"
630   PAUSE
640   IF Count_out=1 THEN
650     ASSIGN @Path1 TO "Lod"
660     ASSIGN @Path2 TO "Dia"
670 !   ASSIGN @Path3 TO "Stk"
680 !   ASSIGN @Path4 TO "Itime"
690   END IF
700   IF Count_out=2 THEN
710     ASSIGN @Path5 TO "Stress"
720   END IF
730   IF Count_out=2 OR 4 THEN
740     ASSIGN @Path6 TO "Strain"
750   END IF
760   IF Count_out=3 THEN
770     ASSIGN @Path7 TO "Lstress"
780   END IF
790   IF Count_out=3 OR 5 THEN
800     ASSIGN @Path8 TO "Lstrain"
810   END IF
820   IF Count_out=4 THEN
830     ASSIGN @Path9 TO "Cstress"
840   END IF
850   IF Count_out>=5 THEN
860     ASSIGN @Path10 TO "Clstress"
870 !   ASSIGN @Path11 TO "Strainp"
880   END IF
890   IF Count_out=6 THEN
900     ASSIGN @Path12 TO "Lstrainp"
910   END IF
920   OFF KEY
930   PRINTER IS 1
940   PRINT "ENTERING  ASSIGNED PATHS"
950   FOR I=1 TO Rdg
960     IF Count_out=1 THEN
970       ENTER @Path1;Lod(I)
980       ENTER @Path2;Dia(I)
990 !     ENTER @Path3;Stk(I)
1000!     ENTER @Path4;Itime(I)
1010    END IF
1020    IF Count_out=2 THEN
1030      ENTER @Path5;Stress(I)
1040      ENTER @Path6;Strain(I)
1050    END IF
1060    IF Count_out=3 THEN
1070      ENTER @Path7;Lstress(I)
1080    END IF
1090    IF Count_out=3 OR 5 THEN
1100      ENTER @Path8;Lstrain(I)
1110    END IF
1120    IF Count_out=4 THEN
1130      ENTER @Path9;Cstress(I)
1140    END IF
1150    IF Count_out>=5 THEN
1160      ENTER @Path10;Clstress(I)
1170!     ENTER @Path11;Strainp(I)
1180    END IF
1190    IF Count_out=6 THEN
1200      ENTER @Path12;Lstrainp(I)
```

```
1210     END IF
1220   NEXT I
1230   !OUTPUT THE DATA
1240 Dat_out:!
1250   PRINT "SELECT HARD OR SOFT COPY"
1260   BEEP 900..5
1270   IF Count_out=1 THEN PRINT "LOAD/DISP"
1280   IF Count_out=2 THEN PRINT "STRESS/STRAIN"
1290   IF Count_out=3 THEN PRINT "LSTRESS/LSTRAIN"
1300   IF Count_out=4 THEN PRINT "CSTRESS/STRAIN"
1310   IF Count_out=5 THEN PRINT "CLSTRESS/LSTRAIN"
1320   IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
1330   PRINT
1340 Plotz:   !
1350    DEG
1360    OFF KEY
1370    PRINT "Choose whether or not to plot"
1380    ON KEY 4 LABEL "NO PLOT" GOTO N_p
1390    ON KEY 0 LABEL "YES PLOT" GOTO Y_p
1400    GOTO 1400
1410 Y_p:  ! PLOT ROUTINE
1420    OFF KEY
1430    GCLEAR
1440    GINIT
1450    GRAPHICS ON
1460    PLOTTER IS 705,"HPGL"
1470    VIEWPORT 13.5,133.0,10.5,95.0
1480    PEN 1
1490    VIEWPORT 25,110,30,85
1500    IF Count_out=1 THEN !MAX COORDINATES FOR LOD VS. DIA DISPLACEMENT
1510       Max_x=.10
1520       Max_y=10
1530        Y_step=10
1540      WINDOW 0,Max_x,0,Max_y
1550      AXES Max_x/10,Max_y/Y_step,0,0
1560    END IF
1570    IF Count_out=2 THEN !MAX COORDINATES FOR  STRESS/STRAIN
1580       Max_x=1.0
1590       Max_y=200
1600        Y_step=10
1610      WINDOW 0,Max_x,0,Max_y
1620      AXES Max_x/10,Max_y/Y_step,0,0
1630    END IF
1640    IF Count_out=3 THEN !MAX COORDINATES FOR LOG STRESS/STRAIN
1650       Max_x=-3.0
1660       Max_y=2.5
1670        Y_step=10
1680      WINDOW Max_x,0,.01,Max_y/.995
1690      AXES Max_x/6,Max_y/Y_step,Max_x,.01
1700    END IF
1710    IF Count_out=4 THEN !MAX COORDINATES FOR C STRESS/STRAIN
1720       Max_x=1.0
1730       Max_y=250
1740        Y_step=10
1750      WINDOW 0,Max_x,0,Max_y
1760      AXES Max_x/10,Max_y/Y_step,0,0
1770    END IF
1780    IF Count_out=5 THEN !MAX COORDINATES FOR CLSTRESS/LSTRAIN
1790       Max_x=-3.0
1800       Max_y=2.5
```

```
1810      Y_step=5
1820     WINDOW Max_x,0,.01,Max_y/.995
1830     AXES Max_x/6,Max_y/Y_step,Max_x,.01
1840   END IF
1850   IF Count_out=6 THEN !MAX COORDINATES FOR CLSTRAIN/CLSTRESS
1860     Max_x=-4.0
1870     Max_y=2.5
1880     Y_step=5
1890     WINDOW Max_x,0,.01,Max_y/.995
1900     AXES Max_x/8,Max_y/Y_step,Max_x,.01
1910     END IF
1920   CSIZE 2.0
1930   VIEWPORT 13.5,133,10.5,95
1940   LORG 4
1950   IF Count_out=1 THEN
1960   FOR I=0 TO Max_x STEP Max_x/10
1970      MOVE I,-Max_y/20
1980      LABEL USING "K";I
1990      NEXT I
2000   MOVE Max_x/2,-Max_y/8
2010   END IF
2020   IF Count_out=2 THEN
2030   FOR I=0 TO Max_x STEP Max_x/10
2040      MOVE I,-Max_y/20
2050      LABEL USING "K";I
2060      NEXT I
2070   MOVE Max_x/2,-Max_y/8
2080   END IF
2090   IF Count_out=3 THEN
2100      FOR I=0 TO Max_x STEP Max_x/6
2110        MOVE I,-Max_y/20
2120        LABEL USING "K";I
2130        NEXT I
2140     MOVE Max_x/2,-Max_y/8
2150   END IF
2160   IF Count_out=4 THEN
2170   FOR I=0 TO Max_x STEP Max_x/10
2180      MOVE I,-Max_y/20
2190      LABEL USING "K";I
2200      NEXT I
2210   MOVE Max_x/2,-Max_y/8
2220   END IF
2230   IF Count_out=5 THEN
2240      FOR I=0 TO Max_x STEP Max_x/6
2250        MOVE I,-Max_y/20
2260        LABEL USING "K";I
2270        NEXT I
2280     MOVE Max_x/2,-Max_y/8
2290   END IF
2300   IF Count_out=6 THEN
2310      FOR I=0 TO Max_x STEP Max_x/8
2320        MOVE I,-Max_y/20
2330        LABEL USING "K";I
2340        NEXT I
2350   MOVE Max_x/2,-Max_y/8
2360   END IF
2370     CSIZE 3.0
2380   IF Count_out=1 THEN LABEL USING "K":"Diametral Displacement, in."
2390   IF Count_out=2 THEN LABEL USING "K":"True Strain, in/in"
2400   IF Count_out=3 THEN LABEL USING "K":"Log True Strain"
```

```
2410   IF Count_out=4 THEN LABEL USING "K";"True Strain"
2420   IF Count_out=5 THEN LABEL USING "K";"Log True Strain"
2430   IF Count_out=6 THEN LABEL USING "K";"Log Plastic"
2440   IF Count_out=6 THEN
2450      MOVE Max_x/2.-Max_y/5
2460      LABEL USING "K";"True Strain"
2470   END IF
2480   LORG 8
2490   CSIZE 2
2500      IF Count_out=1 THEN
2510        FOR I=0 TO Max_y STEP Max_y/Y_step
2520          MOVE -Max_x/40.I
2530          LABEL USING "K";I
2540        NEXT I
2550      END IF
2560      IF Count_out=2 THEN
2570        FOR I=0 TO Max_y STEP Max_y/Y_step
2580          MOVE -Max_x/40.I
2590          LABEL USING "K";I
2600        NEXT I
2610      END IF
2620      IF Count_out=3 THEN
2630        FOR I=0 TO Max_y STEP Max_y/Y_step
2640          MOVE Max_x/.99.I
2650          LABEL USING "K";I
2660        NEXT I
2670      END IF
2680      IF Count_out=4 THEN
2690        FOR I=0 TO Max_y STEP Max_y/Y_step
2700          MOVE -Max/35,I
2710          LABEL USING "K";I
2720        NEXT I
2730      END IF
2740      IF Count_out>=5 THEN
2750        FOR I=0 TO Max_y STEP Max_y/Y_step
2760          MOVE Max_x/.99.I
2770          LABEL USING "K";I
2780        NEXT I
2790      END IF
2800   CSIZE 3.0
2810   LDIR 90
2820   LORG 6
2830   IF Count_out=1 THEN
2840     MOVE -Max_x/10,Max_y/2
2850   END IF
2851   IF Count_out=2 THEN
2852     MOVE -Max_x/8.Max_y/2
2853   END IF
2860   IF Count_out=3 THEN
2870     MOVE Max_x/.90.Max_y/2
2880   END IF
2890   IF Count_out=4 THEN
2900     MOVE -Max_x/10.Max_y/2
2910   END IF
2920   IF Count_out>=5 THEN
2930     MOVE Max_x/.91,Max_y/2
2940   END IF
2950   IF Count_out=1 THEN LABEL USING "K";"Load. Kip"
2960   IF Count_out=2 THEN LABEL USING "K";"True Stress. Ksi"
2970   IF Count_out=3 THEN LABEL USING "K";"Log True Stress(Ksi)"
```

```
2980  IF Count_out=4 THEN LABEL USING "K";"Corrected True Stress(Ksi)"
2990  IF Count_out>=5 THEN LABEL USING "K";"Log True Stress(Ksi)"
3000  IF Count_out>=5 THEN
3010    MOVE Max_x/.88,Max_y/2
3020    LABEL USING "K";"Corrected"
3030  END IF
3040  LDIR 0
3050  LORG 5
3060  CSIZE 1.5
3070  PENUP
3080  IF Count_out<3 THEN
3090    MOVE 0,0
3100  END IF
3110  IF Count_out=3 THEN
3120  PENUP
3130  END IF
3140  IF Count_out=4 THEN
3150    MOVE 0,0
3160  END IF
3170  IF Count_out=5 THEN
3180  PENUP
3190  END IF
3200  IF Count_out=6 THEN
3210    PENUP
3220  END IF
3230 ! PLOT THE VARIOUS CURVES
3240  FOR J=1 TO Rdg
3250    IF Count_out=1 THEN
3260      DRAW Dia(J),Lod(J)
3270    END IF
3280    IF Count_out=2 THEN
3290      DRAW Strain(J),Stress(J)
3300    END IF
3310  NEXT J
3320    IF Count_out=3 THEN
3330      FOR J=1 TO Rdg
3340        MOVE Lstrain(J),Lstress(J)
3350        DRAW Lstrain(J),Lstress(J)
3360      NEXT J
3370  ! PLOT FRACTURE POINT
3380    MOVE Lfstrain,Lfstress
3390    LABEL USING "K";"*"
3400    END IF
3410    IF Count_out=4 THEN
3420      FOR J=1 TO Rdg
3430        DRAW Strain(J),Cstress(J)
3440      NEXT J
3450  !PLOT FRACTURE POINT
3460      MOVE Fstrain,Cfstress
3470      LABEL USING "K";"*"
3480      END IF
3490    IF Count_out=5 THEN
3500      FOR J=5 TO Rdg
3510        MOVE Lstrain(J),Clstress(J)
3520        DRAW Lstrain(J),Clstress(J)
3530      NEXT J
3540 ! PLOT FRACTURE POINT
3550       MOVE Lfstrain,Clfstress
3560       LABEL USING "K";"*"
3570    END IF
```

```
3580   IF Count_out=6 THEN
3590 ! THIS ROUTINE PLOTS LOG CORRECTED TRUE STRESS VS. LOG PLASTIC TRUE
3600     FOR J=27 TO Rdg ! J= THE FIRST PLASTIC STRAIN >.001 LOG TRUE STR
3610 ! THIS VALUE MUST BE ENTERED FOR EACH SPECIMEN
3620         MOVE Lstrainp(J),Clstress(J)
3630         DRAW Lstrainp(J),Clstress(J)
3640       NEXT J
3650 ! PLOT FRACTURE POINT
3660        MOVE Lfstrainp,Clfstress
3670        LABEL USING "K";"*"
3680     END IF
3690    PEN Up
3700  ! GRAPH TITLE
3710    VIEWPORT 13.5,133.0,10.5,95.0
3720    LDIR 0
3730    CSIZE 4
3740    MOVE Max_x/2,Max_y/.90
3750    INPUT "ENTER SPECIMEN NO.",No
3760    LABEL USING "K";"HSLA-100 HOURGLASS"
3770    MOVE Max_x/2,Max_y/.95
3780    LABEL USING "K";"SPECIMEN NO.",No
3790    PENUP
3800  IF Count_out=1 THEN PRINT "LOAD/DISP"
3810  IF Count_out=2 THEN PRINT "STRESS/STRAIN"
3820  IF Count_out=3 THEN PRINT "LSTRESS/LSTRAIN"
3830  IF Count_out=4 THEN PRINT "CSTRESS/STRAIN"
3840  IF Count_out=5 THEN PRINT "CTSTRESS/LSTRAIN"
3850  IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
3860  ON KEY 0 LABEL "HARD COPY" GOTO Har
3870  ON KEY 4 LABEL "SOFT COPY" GOTO Sof
3880 Stop_idle:   GOTO Stop_idle
3890 Har: PRINTER IS 706
3900 Sof:!
3910  OFF KEY
3920  IF Count_out=1 THEN
3930  PRINT "  I           LOAD      DISPL      STROKE     TIME"
3940  PRINT "              (KIP)     (IN)       (IN)       (SEC)"
3950  FOR I=1 TO Rdg
3960    PRINT USING Fmt1:I,Lod(I),Dia(I),Stk(I),Itime(I)
3970    NEXT I
3980    END IF
3990  IF Count_out=2 THEN
4000  PRINT "  I           STRESS     STRAIN "
4010  PRINT "              (Ksi)      (In/In) "
4020  FOR I=1 TO Rdg
4030   PRINT USING Fmt2:I,Stress(I),Strain(I)
4040   NEXT I
4050  END IF
4060  IF Count_out=3 THEN
4070  PRINT "  I           LSTRESS   LSTRAIN "
4080  FOR I=5 TO Rdg
4090    PRINT USING Fmt2:I,Lstress(I),Lstrain(I)
4100    NEXT I
4110  END IF
4120  IF Count_out=4 THEN
4130  PRINT " I            CSTRESS   STRAIN"
4140  FOR I=1 TO Rdg
4150    PRINT USING Fmt2:I,Cstress(I),Strain(I)
4160  NEXT I
4170  END IF
```

```
4180  IF Count_out=5 THEN
4190  PRINT " I          CLSTRESS   LSTRAIN"
4200  FOR I=5 TO Rdg
4210    PRINT USING Fmt2;I,Clstress(I),Lstrain(I)
4220  NEXT I
4230  END IF
4240  IF Count_out=6 THEN
4250  PRINT " I          CLSTRESS   LSTRAINP "
4260  FOR I=23 TO Rdg
4270    PRINT USING Fmt2;I,Clstress(I),Lstrainp(I)
4280  NEXT I
4290  END IF
4300 Fmt1: IMAGE DDD.5X.2(1X.SD.DDDE)
4310 Fmt2: IMAGE DDD.5X.2(1X.SD.DDDE)
4320 N_p:  !
4330  OFF KEY
4340  IF Count_out<6 THEN GOTO Stopper
4350  ASSIGN @Path1 TO *
4360  ASSIGN @Path2 TO *
4370  ASSIGN @Path3 TO *
4380  ASSIGN @Path4 TO *
4390  ASSIGN @Path5 TO *
4400  ASSIGN @Path6 TO *
4410  ASSIGN @Path7 TO *
4420  ASSIGN @Path8 TO *
4430  ASSIGN @Path9 TO *
4440  ASSIGN @Path10 TO *
4450  ASSIGN @Path11 TO *
4460  ASSIGN @Path12 TO *
4470  OFF KEY
4480  ON KEY 4 LABEL "Stop" GOTO S_10
4490  ON KEY 0 LABEL "RERUN" GOTO 330
4500 Pause_idle:  GOTO Pause_idle
4510 S_10:STOP
4520 PRINT "PROGRAM COMPLETED"
4530    END
```

APPENDIX F

BASIC COMPUTER PROGRAM FOR CONSTITUTIVE EQUATION TESTING

```
1       !*****************************************
3       ! PROGRAM STORED AS "POWERFIT"           *
10      ! THE PURPOSE OF THIS PROGRAM IS TO PLOT  *
11      ! LOG BRIDGEMAN CORRECTED TRUE STRESS VS  *
12      ! THE PURPOSE OF THE PROGRAM IS:          *
13      !   1.TO APPLY A POWER FUNCTION FIT BY THE *
14      !     METHOD OF LEAST SQUARES, TO THE LOG  *
15      !     BRIDGEMAN CORRECTED TRUE STRESS/LOG  *
16      !     PLASTIC TRUE STRAIN VALUES FOR EACH  *
17      !     HSLA-100 STEEL SPECIMEN TESTED.      *
18      !   2.COMPUTATION OF THE STRAIN HARDENING  *
19      !     EXPONENT,M, AND THE STRENGTH         *
20      !     COEFFICIENT,K1. PLOT A STRAIGHT LINE *
21      !     BETWEEN LOG PLASTIC STRAIN =.001 AND *
22      !     1.0 USING SLOPE,M, AND INTERCEPT LOG *
23      !     K1. THIS LINE OVERLAYS THE PLOT OF   *
24      !     BRIDGEMAN CORRECTED TRUE STRESS VS.  *
25      !     LOG PLASTIC TRUE STRAIN.             *
26      !   3.COMPUTE THE CORRELATION COEFFICIENT,R*
27      !     AS A MEASURE OF THE FIT BETWEEN THE  *
28      !     TWO CURVES.                          *
29      !   4.ARRAY VALUES CAN BE PRINTED OUT      *
31      !*****************************************
32      !
33      !POWER EQ. FORM LOG(STRESS)=LOG(K1) + MLOG(STRAIN)
34      ! STRESS IS THE BRIDGEMAN CORRECTED TRUE STRESS
40      ! STRAIN IS THE TRUE PLASTIC STRAIN
50      ! THE EXPERSSION SHOULD YIELD A LINEAR RELATION
60      ! M IS THE SLOPE OF THE LINE AND IS CALLED THE STRAIN HARDENING EXPONENT
70      !INTERCEPT CALCULATIONS YIELD THE VALUE FOR K1
71      ! DIMENSION ARRAYS
80      DIM Clstress(500),Lstrainp(500)
90 PRINT "ENSURE APPROPRIATE FILE NO. IS FOLLOWING THE Clstress/Lstrainp arrays"
100 PRINT
110 PRINT " APPROPRIATE DATA DISC MUST BE INSTALLED TO RUN PROGRAM"
120! CALCULATE BRIGEMAN CORRECTION AT FRACTURE CORRF
130 INPUT "FINAL SPECIMEN RADIUS,Rn",Rn
140 INPUT "FINAL NECKED RADIUS OF CURVATURE,R",R
150 Corrf=1/((1+2*R/Rn)*(LOG(1+Rn/(2*R))))
160 PRINT "FINAL CORRECTION FACTOR =";Corrf
161 ! THE BRIDGEMAN CORRECTION TO POINTS 1-RDG
162 ! HAS BEEN DETERMINED AND APPLIED IN CSTRESS
163 ! WHEN THE CSTRESS ARRAY WAS GENERATED.
164 ! THEN THE LGT OF THOSE ARRAY POINTS WAS TAKEN
165 ! TO YIELD THE CLSTRESS ARRAY.
166 ! THESE MANIPULATIONS WERE DONE BY "JHREDUCE"
167 ! THUS THE CLSTRESS ARRAY IN THIS PROGRAM
168 ! HAS THE CORRECTED VALUES IN IT
169 !
170 ! DETERMINE THE FRACTURE POINT
171 ! CORRECTED LSTRESS/LSTRAINP VALUES
173 INPUT "YOUNG'S MODULUS,YM IN Ksi",Ym
174 INPUT "INITIAL SPECIMEN DIAMETER",D_0
175       A_0=(PI/4)*(D_0^2)
176       D_f=2*Rn
177       A_f=(PI/4)*(D_f^2)
178 INPUT "LOAD AT FRACTURE",Flod
179       Fstress=Flod/A_f
180       Fstrain=LOG(A_0/A_f)
181       Cfstress=Corrf*Fstress
```

```
184        Lcfstress=LGT(Cfstress)
185        Fstrainp=Fstrain-(Cfstress/Ym)
188        Lfstrainp=LGT(Fstrainp)
189        PRINT "LCFSTRESS=",Lcfstress
190        PRINT "LFSTRAINP =",Lfstrainp
192    ASSIGN @Path1 TO "Clstress5"
193    ASSIGN @Path2 TO "Lstrainp5"
200    INPUT "SPECIFY NUMBER OF ARRAY POINTS 500 MAX",Rdg
210    FOR I=1 TO Rdg
220       ENTER @Path1;Clstress(I)
230       ENTER @Path2;Lstrainp(I)
240    NEXT I
250    !OUTPUT DATA
260    PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
270    PRINT "THE Lstrainp and Clstress arrays"
280    OFF KEY
290    ON KEY 0 LABEL "HARD COPY" GOTO Har1
300    ON KEY 4 LABEL "SOFT COPY" GOTO Sof1
310 Stop_idle:    GOTO Stop_idle
320 Har1:   PRINTER IS 706
330 Sof1: !
340    OFF KEY
350    PRINT "I     CLSTRESS     LSTRAINP"
360    FOR I=1 TO Rdg
370       PRINT USING Fmt1;I;Clstress(I),Lstrainp(I)
380    NEXT I
390 Fmt1: IMAGE DDD,5X,2(1X,SD.DDDE)
400 ! FIT A STRAIGHT LINE TO THE ORDERED PAIRS
410 ! Lstrainp(I),Clstress(I)
420 ! SOLVING THE SIMULTANEOUS EQUATIONS AS
430 ! LISTED IN THE CRC HANDBOOK
440 !A AND B ARE THE FRACTURE POINT Lstrainp andClstress values respectively
450 A=Lfstrainp ! FRACTURE POINT LSTRAINP
460 B=Lcfstress !FRACTURE POINT LCFSTRESS
470 C=A*B
480 D=A^2
490 E=0
500 F=B^2
510 G=0
520 N0=1    ! DATA PAIR COUNTER INCLUDES FRACTURE POINT
530 ! THE INITIAL VALUE FOR I IS USER INPUTTED
550 INPUT " FIRST DATA POINT,RDG =",First
551 ! THIS SHOULD BE THE FIRST POINT WITH LSTRAINP
552 ! GREATER THAN -3.0
560   FOR I=First TO Rdg
570     A0=A+Lstrainp(I)
580     A=A0 !NOW A IS SUMMING VARIABLE
590     B0=B+Clstress(I)
600     B=B0 !NOW B IS SUMMING VARIABLE
610     C0=C+(Clstress(I)*Lstrainp(I))
620     C=C0 !NOW C IS SUMMING VARIABLE
630     D0=D+(Lstrainp(I)^2)
640     D=D0 !NOW D IS SUMMING VARIABLE
650     F0=F+(Clstress(I)^2)
660     F=F0 !NOW F IS SUMMING VARIABLE
670     N0=N0+1 !COUNTER FOR DATA PAIRS
680   NEXT I
690   N=N0
691   E=A^2
692   G=B^2
```

```
700   OFF KEY
710   PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
720   PRINT "THE DATA OUTPUT"
730   ON KEY 0 LABEL "HARD COPY" GOTO Har2
740   ON KEY 4 LABEL "SCREEN OUTPUT" GOTO Sof2
750   GOTO 750
760 Har2:PRINTER IS 706
770 Sof2:!
780   INPUT "SPECIMEN NO.=",No
800   INPUT "TEST TEMPERATURE=",Tt
810   PRINT
820   PRINT "       HSLA-100 HOURGLASS"
830   PRINT "       SPECIMEN NO.",No
831   PRINT
840   PRINT "       TEST TEMPERATURE =";Tt;"DEG. C"
850   PRINT
860   PRINT "       YOUNG'S MODULUS =";Ym;" Ksi"
870   PRINT
880   PRINT "       FIRST DATA POINT =",First
890   PRINT
920   !COMPUTE STRAIN HARDENING EXPONENT,K1 AND
930   PRINT
940   !SLOPE OF LINE M
950   PRINT "       NUMBER OF DATA PAIRS=";N
960   M=((N*C)-(A*B))/((N*D)-E)
970   K1=(B/N)-(M*A/N)
980   PRINT
990   PRINT "       SLOPE = ";M
1000  PRINT
1010  PRINT "       INTERCEPT = ";K1
1020  PRINT
1030  ! COMPUTE CORRELATION R
1040  Corcoef=((N*C)-(A*B))/SQR(((N*D)-E)*((N*F)-G))
1050  PRINT "       CORRELATION COEFFICIENT,R =";Corcoef
1060  PRINT
1070  PRINTER IS 1
1080  Count_out=1
1090 Plotz:  !
1100   DEG
1110   OFF KEY
1120   PRINT "Choose whether or not to plot"
1130   ON KEY 4 LABEL "NO PLOT" GOTO N_p
1140   ON KEY 0 LABEL "YES PLOT" GOTO Y_p
1150   GOTO 1150
1160 Y_p:  ! PLOT ROUTINE
1170   OFF KEY
1180   GCLEAR
1190   GINIT
1200   GRAPHICS ON
1210   PLOTTER IS 705,"HPGL"
1220   VIEWPORT 13.5,133.0,10.5,95.0
1230   PEN 1
1240   VIEWPORT 25,110,30,85
1250 !   Max_x=-4.0
1260     Max_x=-3.0
1270     Max_y=2.5
1280     Y_step=5
1290     WINDOW Max_x,0,.01,Max_y/.995
1300     AXES Max_x/6,Max_y/Y_step,Max_x,.01
1310   CSIZE 2.0
```

```
1320    VIEWPORT 13.5.133.10.5.95
1330    LORG 4
1340       FOR I=0 TO Max_x STEP Max_x/6
1350         MOVE I.-Max_y/20
1360         LABEL USING "K":I
1370         NEXT I
1380    MOVE Max_x/2.-Max_y/8
1390      CSIZE 3.0
1400       LABEL USING "K":"Log Plastic"
1410       MOVE Max_x/2.-Max_y/5
1420       LABEL USING "K":"True Strain"
1430    LORG 8
1440    CSIZE 2
1450         FOR I=0 TO Max_y STEP Max_y/Y_step
1460           MOVE Max_x/.99.I
1470           LABEL USING "K":I
1480         NEXT I
1490    CSIZE 3.0
1500    LDIR 90
1510    LORG 6
1520      MOVE Max_x/.91.Max_y/2
1530      LABEL USING "K":"Log True Stress(Ksi)"
1540      MOVE Max_x/.88.Max_y/2
1550      LABEL USING "K":"Corrected"
1560    LDIR 0
1570    LORG 5
1580    CSIZE .5
1590  ! THIS ROUTINE PLOTS LOG CORRECTED TRUE STRESS VS. LOG PLASTIC STRAIN
1600      FOR J=First TO Rdg
1610          MOVE Lstrainp(J),Clstress(J)
1620          DRAW Lstrainp(J),Clstress(J)
1630  !       LABEL USING "K";"*"
1640        NEXT J
1650   PENUP
1660  ! PLOT FRACTURE POINT
1720      CSIZE .5
1760         MOVE Lfstrainp.Lcfstress
1770         LABEL USING "K":"*"
1780  ! PENUP
1790  ! THIS SECTION PLOTS THE CURVE FIT LINE
1800  ! FIRST POINT CORRESPONDS TO A STRAIN OF .001
1810  ! THE SECOND POINT CORRESPONTS TO A STRAIN OF1.0
1820          X1=-3.0
1830          Y1=(M*X1)+K1
1833          MOVE X1.Y1
1840          X2=0
1850          Y2=(M*X2)+K1
1901     BEEP 500..2
1902     PRINT "CHANGE COLOR OF PEN ? 30 SEC DELAY"
1903  !  PRINT "PRESS PEN DOWN"
1905          WAIT 30
1910          DRAW X1.Y1
1911          DRAW X2.Y2
1920   ! GRAPH TITLE
1930     VIEWPORT 13.5.133.0.10.5.95.0
1940     LDIR 0
1950     CSIZE 4
1960     MOVE Max_x/2.Max_y/.90
1970     INPUT "ENTER SPECIMEN NO.".No
1980     LABEL USING "K":"HSLA-100 HOURGLASS"
```

```
1990    MOVE Max_x/2,Max_y/.95
2000    LABEL USING "K";"SPECIMEN NO.",No
2010  PENUP
2020 N_p:  !
2030  OFF KEY
2040  Count_out=Count_out+1
2050  IF Count_out>1 THEN
2060  ASSIGN @Path1 TO *
2070  ASSIGN @Path2 TO *
2080  ELSE
2090  GOTO Plotz
2100  END IF
2110  OFF KEY
2120  PRINTER IS 1
2130  ON KEY 4 LABEL "Stop" GOTO S_10
2140  ON KEY 0 LABEL "RERUN" GOTO 192
2150 Pause_idle:  GOTO Pause_idle
2160 S_10:STOP
2161 PRINT "PROGRAM COMPLETE"
2170    END
```

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